N-TONE SIGMA-DELTA UWB-OFDM TRANSMITTER AND RECEIVER

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ABSTRACT

A new method for generating and detecting the UWB-OFDM signal using a modified sigma-delta modulator is proposed. Unlike narrowband OFDM, the UWB-OFDM spectrum can have gaps between subcarriers. The modified sigma-delta modulator, dubbed N-Tone sigma-delta, introduces N zeros at the frequencies in the quantization noise spectrum. These zeros match the locations of frequencies used by the OFDM system and the quantization noise spectrum fills the gaps in the spectrum of the UWB-OFDM signal. In fact this new structure could be used in other UWB systems anytime we have gaps in the spectrum of transmitted signal. We describe both the transmitter and receiver structures for UWB-OFDM. We also study the spectrum of the underlying system.

1. INTRODUCTION

UWB-OFDM is a novel system that has been proposed as a physical layer for a high bit rate, short-range (10m – 20m) communication network in high performance computing clusters. Traditional Ultra Wideband communications, e.g., [1]-[3], use pulse-amplitude or pulse position modulation and different pulse generation methods, pulse rate and shape, center frequency and bandwidth. Earlier UWB systems were designed to be carrierless. Since the FCC allocated the spectrum 3.1-10.6 GHz for UWB, these systems must be revised to satisfy the FCC power spectral density mask. Most previous time-domain UWB systems are single carrier. This complicates the design of such systems to fit FCC regulations and makes inefficient use of the available spectrum **[4].** In contrast, UWB-OFDM is a multi-carrier UWB system that relies on splitting orthogonal subcarriers in a train of short pulses, sending them over the channel and reassembling them at the receiver to get orthogonality and recover each subcarrier data separately [4]-[6]. This new system offers more flexibility in shaping the transmitted signal spectrum because it has more degrees of freedom. UWB-OFDM provides more multipath resolution than single carrier UWB. A rake receiver can therefore achieve more multipath diversity gain and improve the overall performance. Unlike narrowband OFDM, a given tone in UWB-OFDM is transmitted only during parts of the transmission interval. Reliable communication results from integrating several pulses, and high throughput from transmitting frequencies in parallel.

One of the major differences between UWB-OFDM and narrowband OFDM is their spectral shapes. Unlike narrowband OFDM, IFFT and FFT cannot be used directly to generate and receive UWB-OFDM signals because of the high bit rates involved. Designing fast A/D and D/A converters that handle these signals is an open problem. To solve these problems in this paper, we describe a procedure that moves the bulk of the processing load from the analog section to the digital baseband section. Sigma-Delta A/D and D/A converters are a good choice for high bit rate wireless communication [7]. Traditional version of sigma-delta modulators cannot be used in UWB-OFDM transceivers because they would require prohibitively high sampling rates. In this paper we modify the sigma-delta structure to fit the characteristics of UWB-OFDM signals. This enables us to do most of the processing digitally in both transmitter and receiver. Also we are able to use IFFT and FFT to generate and demodulate UWB-OFDM signals. Finally, this approach gets rid of the high peak to average ratio (PAR) problem that occurs with OFDM systems. All these advantages come at the expense of a lower spectral efficiency, unless one uses more complex multi-band implementations. The new structure could be used in other UWB system where the transmitted signal spectrum has some gaps. The structure of the paper is as follow. In section (2) we review the basic idea as well as the spectrum of UWB-OFDM signaling. The structure of the proposed N-Tone sigma-delta modulator is presented in section (3). Section (4) and (5) show UWB-OFDM transmitter and receiver structures respectively using N-Tone sigma-delta modulation.

2. UWB-OFDM SYSTEM

UWB-OFDM signal is a composite of trains of low duty cycle pulses where each train is modulated with orthogonal subcarriers [4-6]. Each modulated train has the form:

$$f_k(t) = p(t)e^{j2\pi k f_0 t} \quad (1)$$

where $p(t)$ is a coded pulse train that consists of N pulses:

$$p(t) = \sum_{n=0}^{N-1} s(t - nT) e^{-j\frac{2\pi c(n) t}{T_c}} \quad (2)$$

and s(t) is a low pass pulse, such as a square pulse or a Gaussian pulse with duration T_s. Each pulse in the train is coded using a Costa's sequence *c(n)* to achieve better time and frequency properties [4-6]. For simplicity in this paper we use unmodulated rectangular pulses.

With proper selection of the parameters T, T_s, f_0 and N the subcarriers are orthogonal and we can modulate each of them with any kind of well-known modulation schemes like on-off keying, BPSK and QAM. The transmitted signal is:

$$x(t) = \sum_m \sum_{k=1}^{K} b_k^m p(t - nT_t) e^{j2\pi k f_0 (t - mT_t)} \quad (3)$$

where b_k^m is the symbol that is transmitted in the *mth* transmission interval over the *kth* subcarrier.

The selection of the parameters T, T_s, f_0 and N determines the way that we use the spectrum. In synchronous UWB-OFDM these parameters are set as follow [4-5]:

$$T = (N+1)T_s \quad ; \quad f_0 = \frac{1}{NT_s} \cong \frac{1}{T}. \quad (4)$$

This leads to a simple way of generating UWB-OFDM signal at the expense of poor utilization of the available spectrum.

To show this, we can take a look at the spectrum $|P(f)|^2$ of the pulse train *p(t):*

$$|P(f)|^2 = |S(f)|^2 \frac{\sin^2(\pi N f T)}{\sin^2(\pi f T)} \quad (5)$$

Since $s(t)$ is an ultra wideband signal then the bandwidth of $p(t)$ is determined by the second term in equation (5), which is plotted at Figure-1. The first zero occurs at $f=1/NT$. The amplitudes of the peaks that occur at $f = \pm 1/T, \pm 2/T, \ldots$ are multiplied by $|S(f)|^2$. The spectrum of synchronous UWB-OFDM is similar to Figure-1 with a large gap of $1/T$ between subchannels. In order to utilize the spectrum in a better way, we can fill the gaps by using:

$$T > T_s \quad ; \quad f_0 = \frac{1}{NT} \quad (6)$$

which is the most general form of UWB-OFDM described at [6]. We can also consider cases between these two extreme cases where the center frequencies of the sub-channels are separated by multiples of $1/NT$.

Generating and receiving this type of signals is very challenging. The special characteristics of the UWB-OFDM signal require very fast and high-resolution D/A and A/D converters at the transmitter and receiver. Given the rapid advances in digital technology where analog circuitry have much slower improvement in analog RF circuits, it is desirable to move the processing load to digital side as much as possible.

To solve these problems we note that a general UWB-OFDM signal looks like:

$$f_k(t) = p(t)e^{j2\pi k f_0 t} \cong \sum_{n=0}^{N-1} s(t - nT) e^{-j\frac{2\pi k n}{N}} \quad (7)$$

In particular we are dealing with an oversampled signal. This suggests using sigma-delta modulation for D/A and A/D conversion. As mentioned earlier, current versions of sigma-delta modulation cannot be directly used for UWB-OFDM signals because the input is not a lowpass narrowband signal. The signal can be converted to a lowpass signal by using a very high oversampling ratio. However this leads to inefficient use of system resources. In the following section, we introduce a modified sigma-delta modulator named N-Tone sigma-delta modulator that fits the characteristics of the UWB-OFDM signal.

3. SIGMA-DELTA MODULATION

Sigma-Delta modulation is an oversampling structure used for fast high-resolution A/D and D/A converters [8]. It digitizes the input signal to a low amplitude-resolution (usually 1 bit) but high time-resolution (oversampled) stream. Figure-2 shows a discrete-time model of sigma delta modulator. The output of the integrator is digitized to a binary level $(\pm V)$ and generates the output binary stream. Since the loop contains a nonlinear part, its exact analysis is very hard and an approximate linear model of quantizer is used instead [8]. The approximation yields and expression for the output of the sigma-delta modulator:

$$Y(z^{-1}) = X(z^{-1}) + (1 - z^{-1})E(z^{-1}) \quad (8)$$

Figure–3 shows the frequency response of $(1 - z^{-1})$. If the input is a narrowband lowpass signal the amount of noise in that band is very small and most of the quantization noise is out of band and can be removed with proper lowpass filtering. This structure is used for

fast high resolution D/A conversion (Figure-4)[8]. An analog switched-capacitor version of the sigma-delta modulator is also used for A/D conversion (Figure-5)[8]. To get better results, higher order sigma-delta modulators can be used [8].
A careful look at Figure-1 shows that we can think of the synchronous UWB-OFDM as a collection of narrowband signals centered on the center frequencies of subchannels. Therefore we should modify the sigma-delta structure to remove digitization noise away from these frequencies. Figure-7 shows the structure of the modified sigma-delta modulator dubbed an N-tone sigma-delta modulator. If we use an approximate linear model of the system, we can express the output of the loop as:

$$Y(z^{-1}) = X(z^{-1}) + (1 - z^{-N})E(z^{-1}). \qquad (9)$$

In Figure-6 we plot the frequency response of $(1 - z^{-N})$. Higher order N-tone sigma-delta modulator can be also used for getting a better frequency response. This structure can be used for generating and receiving any UWB signal that has sufficient gap in its spectrum.

4. TRANSMITTER STRUCTURE

We illustrate the operation of the system with a QAM example. Similar structures can be used with the other types of modulation. Figure-8 shows the block diagram of an UWB-OFDM transmitter using N-Tone sigma-delta modulator. QAM symbols with rate R enter a serial to parallel converter and are divided into N stream with rate R/N. We insert L zeros between streams and compute an LN point IFFT to generate an over sampled digital OFDM signal. By making a parallel to serial conversion we get a digital OFDM signal with rate LR. Then the in-phase and quadrature components are separated and applied to a N-tone sigma-delta modulator. The outputs of sigma delta modulators are binary streams that carry OFDM signal plus noise. We could filter them properly to remove quantization noise after doing D/A and send them to RF stage. In general, for non-average-power-constrained applications, we can skip this filtering stage and send the binary output of sigma-delta modulators using any single channel binary UWB system. Note that in this case we eliminate the large peak to average power ratio (PAR) problem associated with OFDM systems. Specifically amplifiers need not have a large dynamic range as they process constant amplitude signals.

4. RECIVER STRUCTURE

Receiver structures for UWB-OFDM systems and their performance in the multipath fading channels have been presented in [4-6]. For demodulation signals produced with N-Tone sigma-delta, observe first that we could attempt to detect the analog binary stream in analog domain and convert it to a binary digital stream. The digital stream then can be analyzed using an FFT to recover the data. The disadvantage of this approach is that it cannot exploit multipath effects to achieve more reliable detection. A better approach is to digitize the observation and use optimal or near optimal detection in the digital domain. Specifically we can use N-tone sigma-delta modulator to implement a more digital receiver structure. Figure-9 shows this structure. The input signal is the transmitted signal plus noise that enters an analog version of N-Tone sigma-delta modulator. The output is an approximation of binary sequence generated at the receiver and we can digitally filter it to remove noise. The remaining process is like traditional OFDM and we must downsample the output to get transmitted symbols. The performance of this system is evaluated in an upcoming paper [9].

5. REFERENCES

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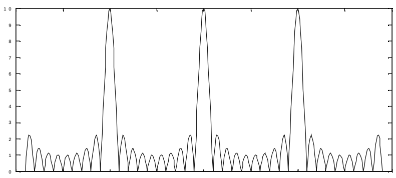

Figure-1 $\left|\dfrac{\sin^2(\pi N T f)}{\sin^2(\pi T f)}\right|$ for N=10

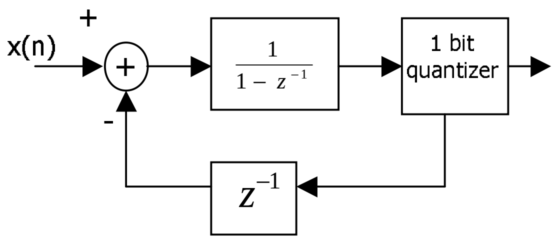

Figure-2 Traditional sigma-delta modulator

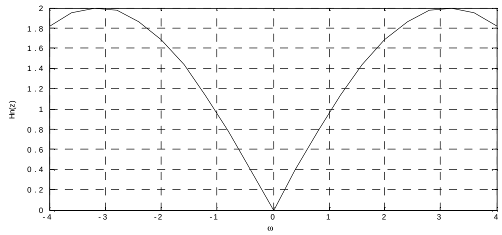

Figure-3 frequency response of traditional sigma-delta modulator to quantization error

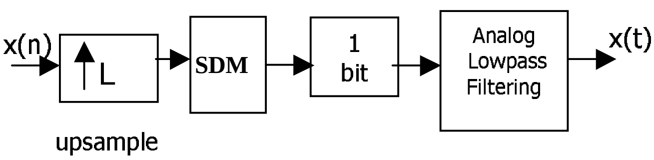

Figure-4 Traditional sigma-delta D/A

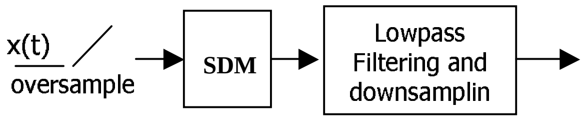

Figure-5 Traditional sigma-delta A/D

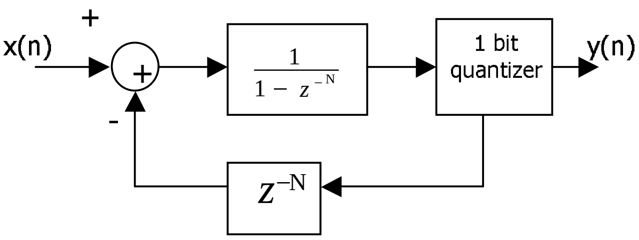

Figure-6 N-Tone Sigma-Delta modulator

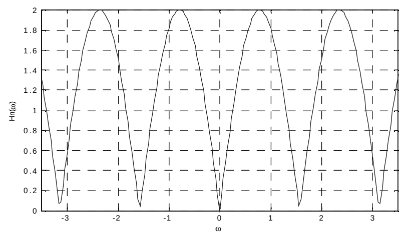

Figure-7 Frequency response of N-Tone sigma-delta modulator to quantization error

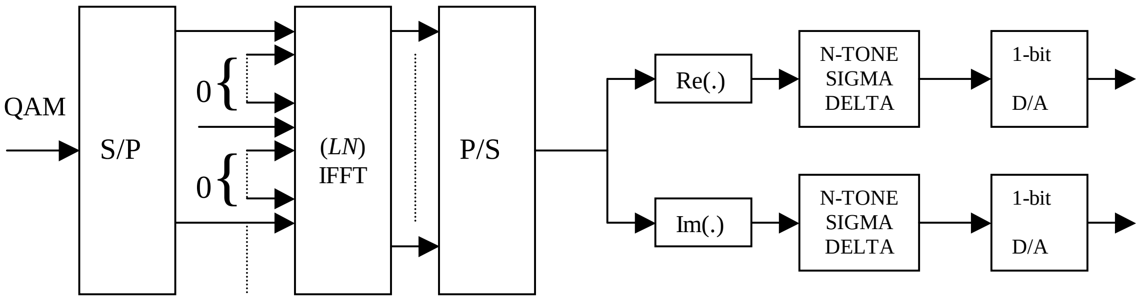

Figure-8 N-Tone sigma-delta UWB-OFDM Transmitter

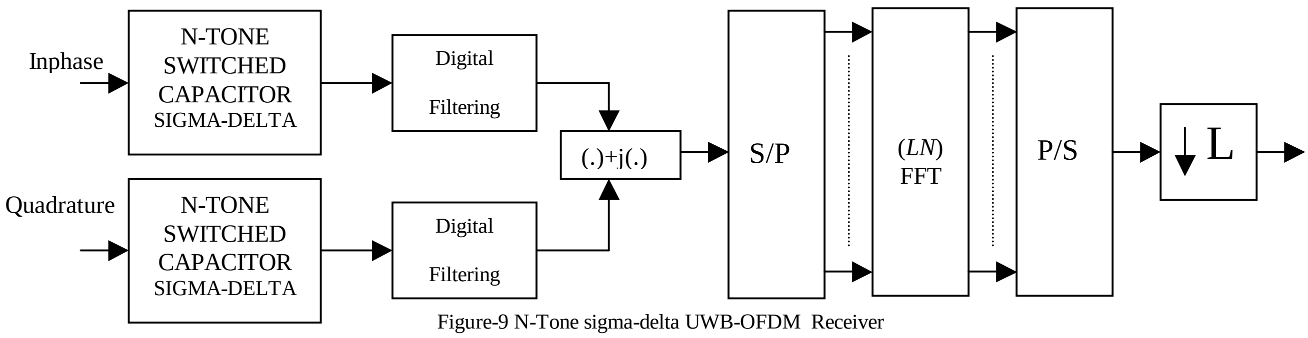

Figure-9 N-Tone sigma-delta UWB-OFDM Receiver