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Fluid Coding in Time Hopping Ultra Wide Band Networks

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***Abstract*—Time Hopping Ultra Wide Band (TH–UWB) commonly encodes the data symbols by shifting the position of the transmitted pulses by a quantity that is quantized over the inter-pulse interval range. In this paper, we relax the hypothesis of a discrete value for the time shift introduced by the TH code, by considering the possibility of generating real-valued codes that introduce time hopping in a "fluid" way. The effect on the power spectral density of generated signals is analyzed, and potential application of fluid coding to multiple access and to network coexistence are discussed, with the awareness of the consequent increased complexity of the receiver,**

***Index Terms*—Ultra Wide Band, Impulse Radio, Time Hopping coding, Multi-User UWB communications**

I. INTRODUCTION

One possible way of generating Ultra Wide Band (UWB) signals is by radiating pulses that are very short in time. This transmission technique goes under the name of Impulse Radio (IR). The way by which the information data symbols modulate the pulses may vary; Pulse Position Modulation (PPM) and Pulse Amplitude Modulation (PAM) are commonly adopted modulation schemes ([1],[2]). In addition to modulation and in order to shape the spectrum of the generated signal, the data symbols are encoded using pseudonoise (PN) sequences. In a common approach, the encoded data symbols introduce a time dither on generated pulses leading to the so-called Time-Hopping UWB (TH-UWB). Direct-Sequence Spread Spectrum (DS-SS), that is, amplitude modulation of basic pulses by encoded data symbols, in the IR version, indicated as Direct-Sequence UWB (DS-UWB), also seems particularly attractive ([3]-[6]).

The main focus of this paper will be given to IR-UWB and specifically to TH-UWB. As well known, in the common case of periodicity of the code coinciding with the bit repetition interval, the power of a TH-UWB signal concentrates at multiples of the bit repetition frequency. The TH-UWB signal is in fact periodic with a period equal to the bit period. Spectral analysis of such signals show that it is not possible to remove all the peaks of the Power Spectral Density (PSD) by only increasing the periodicity of the TH code. To decrease the energy concentration at peaks, one should allow each pulse to assume random positions inside each pulse interval [7]. It is based on this observation that the analysis of the present paper originates. In this work, we relax the hypothesis of considering discrete values for the time shift introduced by the TH code, by considering the possibility of generating real-valued codes that introduce time hopping in a "fluid" way. We analyze the effect on the PSD of a generated signal and propose the application of fluid coding to multiple access.

The paper is organized as follows. Section II introduces the signal format and related expressions for the PSD. Section III focuses on the novel technique of fluid time-hopping. Section IV contains a discussion on possible applications, in particular in multi-user communication networks, and concludes the work.

II. SIGNAL FORMAT

A TH-UWB signal combined with binary PPM can be generated as shown in Fig.1([7]).

Given a binary sequence to be transmitted $\mathbf{b} = (\ldots, b_0, b_1, \ldots, b_k, b_{k+1}, \ldots)$, generated at a rate of $R_b = 1/T_b$ bits/s, a first system repeats each bit N_s times and generates a binary sequence $(\ldots, b_0, b_0, \ldots, b_0, b_1, b_1, \ldots, b_1, \ldots, b_k, b_k, \ldots, b_k, b_{k+1}, b_{k+1}, \ldots, b_{k+1}, \ldots) = (\ldots, a_0, a_1, \ldots, a_j, a_{j+1}, \ldots) = \mathbf{a}$ at a rate of $R_{cb} = N_s/T_b = 1/T_s$ bits/s. This system introduces redundancy and is a $(N_s,1)$ block coder indicated as a repetition coder. A second block called a transmission coder applies an integer-valued code $\mathbf{c} = (\ldots, c_0, c_1, \ldots, c_j, c_{j+1}, \ldots)$ to the binary sequence $\mathbf{a} = (\ldots, a_0, a_1, \ldots, a_j, a_{j+1}, \ldots)$ and generates a new sequence $\mathbf{d}$. The generic element of the sequence $\mathbf{d}$ is expressed as follows:

$$d_j = c_j T_c + a_j \varepsilon \tag{1}$$

where T_c and ε are constant terms that satisfy, for all c_j, the condition $c_j T_c + \varepsilon < T_s - T_m$ where T_m is the duration of the pulse. One also has, in general, $\varepsilon \ll T_c$. T_c is called chip time.

Note that $\mathbf{d}$ is a real-valued sequence as opposed to $\mathbf{a}$, which is binary, and to $\mathbf{c}$, which is integer-valued. For now, we shall follow the most common trend and assume that $\mathbf{c}$ is a pseudorandom code, its generic element c_j being an integer verifying $0 \le c_j \le N_h - 1$. The code $\mathbf{c}$ might be periodic, and in that case, its period is indicated by N_p. Two particular cases are worth discussing. The first corresponds to the absence of periodicity in the code, that is, $N_p \rightarrow \infty$, and the second to $N_p = N_s$. In the second case, which is the most commonly

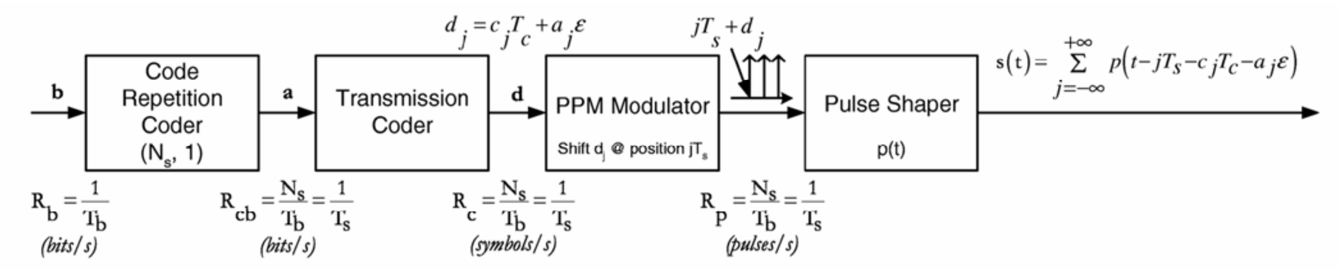

Figure 1 Transmission scheme for a PPM-TH-UWB signal (from Di Benedetto/Giancola, UNDERSTANDING ULTRA WIDE BAND RADIO FUNDAMENTALS, (c)2005, Chapter 2. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, New Jersey).

adopted, the periodicity of the code coincides with the length of the repetition code.

The coded real-valued sequence **d** enters a third system, the PPM modulator which generates a sequence of Dirac pulses $\delta(t)$ at a rate of $R_p = N_s / T_b = 1/T_s$ pulses/s. These pulses are located at times $jT_s + d_j$, and are therefore shifted in time from "standard" positions jT_s by d_j. Note that code **c** introduces a TH shifts on generated pulses. In common practice, the shift introduced by the PPM modulator, $a_j\varepsilon$, is much smaller than the shift introduced by the TH code, c_jT_c.

The last system is the pulse shaper with impulse response *p(t)*, which must be such that the signal at the output of the block is a sequence of strictly non-overlapping pulses.

The signal *s(t)* at the output of the cascade of the above systems can be expressed as follows:

$$s(t) = \sum_{j=-\infty}^{+\infty} p\left(t - jT_s - c_jT_c - a_j\varepsilon\right) \tag{2}$$

Note that the bit interval T_b is: $T_b = N_sT_s$. Also note that in Eq.(2), the term c_jT_c defines pulse randomization or dithering with respect to multiples of T_s. If we represent the time shift introduced by the TH code c_jT_c by a random TH dither η_j, which can be assumed to be distributed between 0 and $T_\eta < T_s - T_m - \varepsilon$, we obtain:

$$s(t) = \sum_{j=-\infty}^{+\infty} p\left(t - jT_s - \eta_j - a_j\varepsilon\right) \tag{3}$$

The global effect of η_j and ε is to introduce a random time shift, distributed between 0 and $T_\eta + \varepsilon < T_s - T_m$, which will be indicated by θ_j leading to the following expression for the transmitted signal:

$$s(t) = \sum_{j=-\infty}^{+\infty} p\left(t - jT_s - \theta_j\right) \tag{4}$$

The PSD of signal of Eq. (4), $P_s(f)$, for $N_p = N_s$, can be found under the hypothesis that the time dither process θ, that incorporates the time shift introduced by the TH code η and the time shift introduced by the PPM modulator ε, is a strict-sense stationary discrete random process, where θ_j are the samples of a strict-sense stationary continuous process and the different θ_j are statistically independent with a common probability density function $w(\theta_j)$. One obtains:

$$P_s(f) = \frac{\left|P(f)\sum_{m=1}^{N_s} e^{-j\left(2\pi f\left(mT_s + \eta_m\right)\right)}\right|^2}{T_b} \cdot \left[1 - \left|W(f)\right|^2 + \frac{\left|W(f)\right|^2}{T_b}\sum_{n=-\infty}^{+\infty}\delta\left(f - \frac{n}{T_b}\right)\right] \tag{5}$$

where *P(f)* is the Fourier Transform of *p(t)*, that is the transfer function of the pulse shaper, and *W(f)* is the Fourier transform of *w* coinciding with the characteristic function of *w* computed in $-2\pi f$:

$$W(f) = \int_{-\infty}^{+\infty} w(s)e^{-j2\pi fs}ds = \left\langle e^{-j2\pi fs}\right\rangle = C\left(-2\pi f\right) \tag{6}$$

Equation (5) shows the effect of the TH code and of the time shift introduced by the PPM modulator, which follows the characteristics of the statistical properties of the source. Note that the discrete component of the spectrum has lines at $1/T_b$. The amplitude of the lines is weighted by the statistical properties of the source represented by $|W(f)|^2$. If p indicates the probability of emitting a 0 bit (no shift) and $1-p$ the probability of emitting a '1' bit (ε shift), one can write:

$$\left|W(f)\right|^2 = 1 + 2p^2\left(1 - \cos\left(2\pi f\varepsilon\right)\right) - 2p\left(1 - \cos\left(2\pi f\varepsilon\right)\right) \tag{7}$$

If the source emits equiprobable symbols 0 and 1, then Eq. (7) simplifies as follows:

$$\left|W(f)\right|^2 = \frac{1}{2}\left(1 + \cos\left(2\pi f\varepsilon\right)\right) \tag{8}$$

Note here that ε is small and therefore the discrete components dominate the spectrum. In the simplifying hypothesis that ε is negligible, Eq. (5) is periodic with period $1/T_b$. Note that Eq. (5) can also be applied to any type of source, not necessarily binary.

III. FLUID TIME-HOPPING CODING

A. *Signal format*

Consider the transmitter structure of Fig.1, but substitute $c_j T_c$ by a real value c_j in the interval $[0, T_s - T_m - \varepsilon]$.

The signal of Eq. (2) becomes:

$$s(t) = \sum_{j=-\infty}^{\infty} p(t - jT_s - c_j - a_j \varepsilon) \tag{9}$$

Note that when going from pseudorandom to fluid coding the parameter N_h becomes irrelevant. In both fluid and discrete cases, codes may be periodic of period N_p.

As obvious, there may be a variety of possibilities in choosing the analog waveform that generates the fluid code. A possible way is to sample a sinewave *c(t)* expressed as:

$$c(t) = \frac{(T_s - T_m - \varepsilon)}{2} \cdot \left[1 + \sin(2\pi f_0 t + \varphi)\right] \tag{10}$$

where the period of the sinewave $1/f_0$ coincides with the period of the code $N_p T_s$, that is $f_0 = 1/(N_p T_S)$. Phase φ falls in the interval [0,2π]. We call function *c(t)* the "code function" and plot an example in Fig.2. Figure 2 shows in the upper plot the sinewave for a fixed set a parameter values, with the sampling instants at multiples of T_s. The lower plot of Fig.2 shows the sequence of pulses that are shifted according to the sample values of the sinewave that represent the fluid coding values.

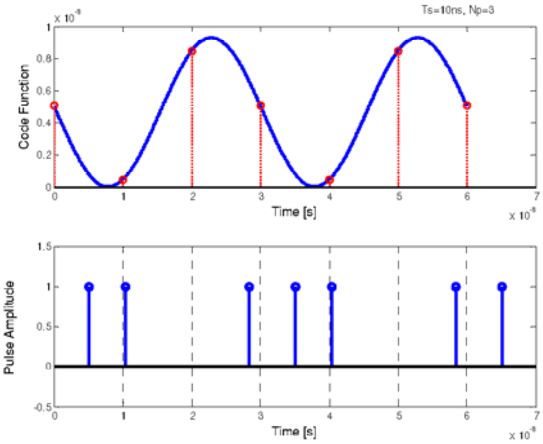

Figure 2 *The upper plot* shows a possible code function represented by a sinewave for T_s=10 ns, N_p=3. The sampling instants at multiples of T_s are highlighted. *The lower plot* shows the train of pulses of a generated signal. Pulse positions are shifted by a fluid value provided by the samples of the code function.

The generic element c_j of the code is thus expressed by:

$$\begin{aligned} c_j = c(jT_s) &= \frac{(T_s - T_m - \varepsilon)}{2} \cdot \left[1 + \sin(2\pi f_0 j T_s + \varphi)\right] = \\ &= \frac{(T_s - T_m - \varepsilon)}{2} \cdot \left[1 + \sin\left(2\pi \frac{j}{N_p} + \varphi\right)\right] \end{aligned} \tag{11}$$

c_j is real and in the interval $[0, T_s - T_m - \varepsilon]$.

As will be further discussed in the next section, note that in case of multi-user communications each user may be assigned with different f_0 or φ value.

B. *Spectrum*

It is straightforward to note that the PSD of the signal of Eq.(9) is given by Eq. (5).

In the present fluid case, spectral lines occur at multiples of $1/(N_p T_S)$, while the maxima at multiples of $1/T_c$ have been eliminated. Therefore, for same power, the fluid case has a better distributed power than the discrete case.

IV. DISCUSSION AND APPLICATION OF FLUID TIME HOPPING TO MULTI-USER COMMUNICATIONS

A. *Discussion on the effect of fluid TH coding on spectrum shaping*

As indicated in Section III, fluid TH coding may be adopted for removing peaks in the PSD of the transmitted signal, with the beneficial effect of distributing power more evenly over the frequency bandwidth. Fluid TH coding enables, therefore, better management of power, while keeping the PSD of the transmitted signal below spectral masks. An example of the application of fluid TH for increasing transmission power, in single-link communications, is shown in Figs. 3 and 4.

Figure 3 represents the PSD of a signal s_1, with total transmitted power $P_{TOT} = -30$ dBm. Signal s_1 adopts a standard discrete pseudorandom TH code, with average pulse repetition period $T_s = 10$ ns, chip time $T_c = 1$ ns, and code period $N_p = 5000$. As expected, the transmitted power for signal s_1 is concentrated at spectral peaks located at multiples of the repetition frequency of the TH sequence, which is here 1 GHz.

Figure 4 represents the PSD of a second UWB signal s_2, with same average pulse repetition period and same total transmitted power as signal s_1, but tending to fluid TH coding. This effect is obtained by significantly decreasing T_c while maintaining same T_s. In particular, the PSD of Fig.4 was obtained by using, T_s =10 ns, T_c=0.1ns. As expected, the introduction of a quasi-fluid TH code has the effect of eliminating peaks in the PSD of the transmitted signal. In particular, we can note on Fig.4 that peak values of the PSD of signal s_2 are about two orders of magnitude smaller than peak values of s_1. Under the hypothesis that transmission power P_{TOT} for signal s_1 was determined in order to meet a given set of emission limitations on transmitted PSDs, we can conclude, therefore, that the adoption of a fluid TH code allows a significant increase in the total transmitted power. In the proposed example, in particular, the gain in transmission power allowed by fluid TH ranges in the order of 20 dB. Such an increase of transmission power corresponds to an increase in the transmission range for a given SNR at the receiver, or to a reduced probability of error for a given distance between transmitter and receiver.

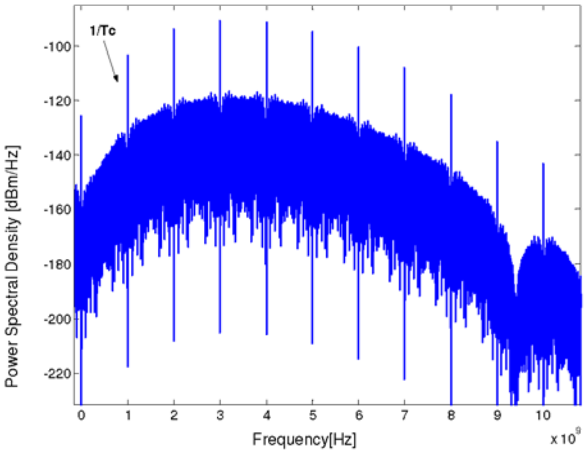

Figure 3 Power Spectral Density of a UWB signal s_1, with standard discrete TH coding.

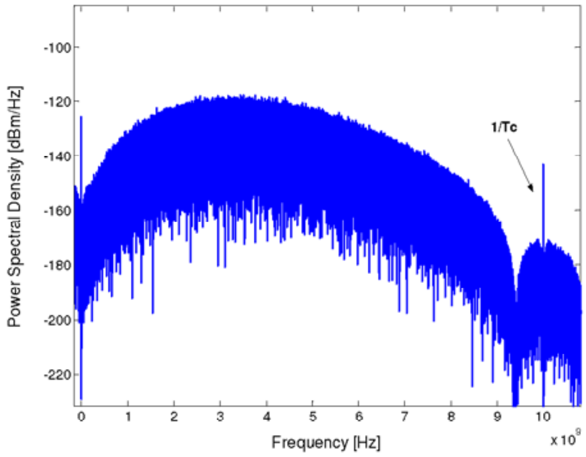

Figure 4 Power Spectral Density of a UWB signal s_2, with fluid pseudorandom TH coding.

B. Application of fluid TH coding to multi-user communications

A possible application of fluid TH coding is to multi-user UWB communications.

Consider, for example, the case of a network of asynchronous binary PPM-TH UWB devices, using same T_S and same code periodicity N_P. Each active link uses a specific fluid code known at both transmitter and receiver. Assume that all transmissions are uncoordinated, that is, codes are randomly generated and independent. With discrete pseudo-random TH codes, we know that transmitted signals have spectral peaks that are located at same frequencies for all active transmissions. As a consequence, the correlator at the receiver also captures a portion of the energy transmitted by other devices, and because of the spectral characteristics of the transmitted signals, the useful energy collected by the correlator is mostly located in correspondence of spectral peaks. Since interfering transmissions concentrate their power at same frequencies, the system is strongly affected by multi-user interference.

A possible way of improving spectral separation among different transmissions is to apply fluid coding, based for example on the sinusoidal code function described in Section III. Multiple access might be implemented by random selection of a different period or phase of the sine wave for each active link of the network. In this way, spectral peaks of different signals locate at different frequencies, with a beneficial reduction in the level of interfering energy at the receiver output

An extension of the above scheme can be introduced for supporting a simple clustering function at the MAC level. In clustered MAC networks, nodes are organized in different subgroups, named *clusters*. Medium access in each cluster is managed independently from other clusters, by defining in general a cluster leader, or *cluster coordinator*, that is in charge of regulating the access of all the other devices of the cluster. In an uncoordinated and asynchronous network, clustering could be easily achieved by separating different clusters with different periods of the sinusoidal fluid TH code. In this way, interference among different subgroups would be better controlled, and cluster coordinators could effectively coordinate access within their cluster without having to take into account interference of devices belonging to foreign clusters.

In the same way, fluid TH coding could be also introduced with the aim of allowing multiple UWB networks to coexist over the same geographical area. The basic idea, in this case, is to reduce mutual interference among different networks by adopting a different set of fluid TH codes for each network. Devices belonging to different networks, in particular, should tune the characteristics of the adopted fluid TH codes, such as periodicity, in order to concentrate transmission powers at different frequencies. Regarding the single network, resource allocation may still be managed with a conventional TH multiple access strategy. The advantage of network separation by fluid coding resides in the possibility of avoiding partitioning the available bandwidth among different networks. With the proposed scheme, network organization may become dynamic: specific nodes in the network could be in charge of scanning the spectrum at network start-up for locating the best locations in the frequency domain where to concentrate transmission power for all devices. At the end of such a preliminary frequency scanning, all the other nodes of the network would be informed of the specific set of parameters that they must adopt for encoding transmission at the physical layer. Note that the proposed approach does not necessarily imply all networks to adopt the same TH coding scheme; The dynamic and smart operational paradigm might be the privilege of a few sophisticated ones.

As a final comment, the adoption of a fluid TH code, as previously pointed out, leads to a more efficient way to deal with emission constraints on transmitted PSDs, if compared to standard discrete TH coding. On the other hand, it has been observed by Nakache and Molisch in [8] that by dividing the inter-pulse interval into an increased number of sub-intervals significantly complicates receiver design. This comment fully applies to the present case of analogue code values. Besides synchronizing in an analogue way on the first pulse of a transmission, the correlator at the receiver must then adjust and match the following pulses. Further investigation should lead to a satisfactory trade-off between suppression of the peaks in the PSD and receiver complexity.

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