Distributed-Based Transversal Filter Approach for Spectrally Encoded Multi-Gb/s CDMA Systems

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Abstract. A novel distributed transversal filter technique for code division multiple access systems is proposed. It is observed that the distributed amplifier principle underlying the filter approach enables the generation of multi-gigahertz waveforms with suitable accuracy. The DTF method is considered in the context of phase-addressing code division multiplexing systems. Simulation results based on a full layout design illustrate the viability of the approach.

Keywords. Distributed transversal filter, code division multiple access, spread time coding, periodic correlation.

Método de filtro transversal basado en el principio de amplificación distribuida para sistemas CDMA con codificación espectral en el régimen de multi-Gb/s

Resumen. En este artículo, se propone una técnica de filtro transversal distribuido para el diseño de sistemas de multicanalización por división de código (CDMA). Se muestra que el principio de amplificación distribuida, método en el que se basa el filtro transversal, permite la generación de formas de onda en el régimen de multi-gigahertz con una adecuada exactitud. El método es considerado en el contexto de sistemas de multicanalización con codificación y decodificación de fase. Resultados de simulación de un diseño completo a nivel de layout ilustra la viabilidad del método propuesto.

Palabras clave. Filtro transversal distribuido, acceso múltiple por división de código y codificación de dispersión en tiempo.

1 Introduction

Owing to its excellent performance for sub-nanometer pulse shaping applications, monolithic integrated transversal filters based on distributed amplifier principles have been considered as a building circuit for the analog interface of high-speed digital communication systems. Detailed studies in [1] established the existing analogy between distributed amplifier and transversal filter topologies thereby demonstrating for the first time pulse shaping capabilities embedded in the preamplifier of a 40 Gb/s front-end optical receiver. In fairly recent developments, distributed transversal filtering has been proposed to perform encoding and correlation as used in Optical Code Division Multiplexing Access (OCDMA) [2, 4]. For such networks, encoding and decoding functions are shifted into the electrical domain by making use of high-speed microwave integrated circuit solutions. On the other hand, optical processing has been considered for seamless encoding of ultra-high speed pulses; however, its development at a wide scale is yet incomplete either due to the high cost incurred in their deployment [5] or due to low reliability to perform encoding functions [4, 6].

In previous proposals based on the DTF method [2, 4], the CDMA receiver consists basically of the correlator while subsequent data recovering circuits are not included in the structure. Nonetheless, an effective decoding of CDMA signals relies to a great extent on the operation of data recovering circuits in a way similar to performance considerations for the receiver comprising optical correlation and subsequent electrical processing [7]. This is because the synchronous operation of the transversal filter requires detection circuits to operate at the chip rate; consequently, the electronic bandwidth of the postdetection receiver is dictated by the chip rate. Following this consideration, the use of DTF as a multi-Gchip/s correlator in an electrical CDMA system must require successive electronic circuits to work at the chip rate. A cost-effective solution should encompass data detection circuits limited to low-complexity functions, such as comparison against a threshold level. Other functions such as sampling pulses at the chip interval and high-speed clock signal generation would be prone to limited jitter budget and large power consumption that render the CDMA system costly and perhaps not competitive with other multiplexing alternatives.

Up to now, distributed-based transversal filtering has been considered for direct sequence (DS) CDMA systems. A first contribution in this area was the design of a monolithic DTF aimed to work as a high-rate sequence receiver [2]. It shows that data reception with zero intersymbol interference (ISI) can be achieved with reconfigurable DTF-based receivers. Practical design considerations allow setting a balance between code length and accuracy in the waveform generation. In another proposal reported in [3], code dictates the filter design as delay between gain cells is non-uniform according to the sequence to be implemented. Distributed gain cells synthesize only ‘1’ positive pulses reducing device loading and losses on transmission lines.

More recently, a practical implementation was reported in [4] demonstrating OCDMA optical access networks operating at 1.25Gb/s and 18Gchip/s. In this approach, user data is encoded using Gold codes of length 7. User data is decoded using reconfigurable filters that achieve bipolar reception of unipolar pulses. The viability of such system was assessed by obtaining a correlation peak from the desired transmitter higher than the correlation from one undesired transmitter achieving error-free detection of encoded data.

This article introduces a coding method suitable for DTF-based CDMA systems that circumvents the need for data recovering circuits operating at chip-rate speeds. The approach makes use of Spread Time (ST) coding. We show herein that the “spectral” coding allows creating orthogonal channels and is compatible with the characteristics of the DTF as predicted by full layout simulations. The Spread Time coding technique of ultra-short light pulses was first proposed by Salehi *et al.* in [8] as an alternative to DS-OCDMA systems. Crespo *et al.* [9] extended the ST coding technique to wireless systems and made comparisons between DS and ST CDMA systems in terms of bandwidth, spectra and noise performance. Practical issues concerning the hardware that enables encoding suggest that the “spectral” encoder can be implemented by synthesizing a filter with a spread-in-time response function. In this approach, the filter output conveys code information on the phases of the waveform subbands instead of impressing codes on the amplitudes of the CDMA signal as in DS systems.

Figure 1 illustrates the application of the DTF method for encoding and decoding high-speed CDMA signals as used in an optical passive network. The CDMA signals are coded and detected non-coherently using an intensity modulation and direct detection scheme. Nodes in the network are connected through a passive coupler (not shown in Fig. 1). Transmission of user data includes choosing a unique code sequence which represents the address of the intended node receiver. The encoded data signal is directly coupled into the input single-mode fiber and broadcast to all receivers. The crosstalk between users is the main source of interference in the CDMA network and is termed as Multi-Access Interference (MAI).

At the intended node receiver, data is decoded by correlation. A fixed code is stored in a matched filter implemented in the form of tapped delay lines. As shown in following sections, the matched filtering is achieved by a broadband distributed amplifier that owns an analogy to the transversal filter topology. The intended receiver must be able to extract its address sequence and discriminate other transmitter addresses. The amplitude peak of the correlation is extracted by threshold devices.

Other environment in which the DTF-based CDMA system can fit is networks impaired by crosstalk, for instance, chip-to-chip interconnects

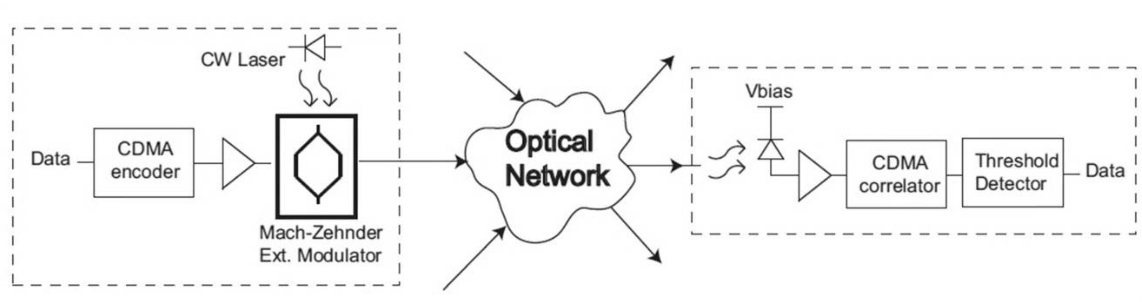

Fig. 1. Passive optical access network using transversal filters as encoders and correlators. The Mach-Zehnder modulator modules light from a continuous wave (CW) Laser

where the high density of electronic devices and tight restriction in layout area give rise to small separation between parallel bus lines. The CDMA approach can be a prospective method to add isolation between tightly coupled buses. Other schemes can be envisaged by including a coupler to combine signals prior transmission over a single channel, as shown in Fig. 2. Here output buffers transmit binary data by modulating the amplitude of short pulses which in turn are applied to the input of encoders. Such filters are reconfigurable by applying appropriate dc voltages to cells so that the response of each transmitter is set according to a signature waveform of the intended node receiver in the network. Encoded signals are broadcast to all receivers and decoders of sample input data or reject in-phase interference by making use of successive comparison against a threshold level. The receiver includes an input buffer that has an integration constant equal to the bit interval T and subsequent data recovering circuits operate at a bit-rate speed.

The DTF as a processor that performs encoding and convolution functions (assuming an ideal channel function between the transmitters and receivers) is analyzed. Details on the transient performance of an 8-tap monolithic

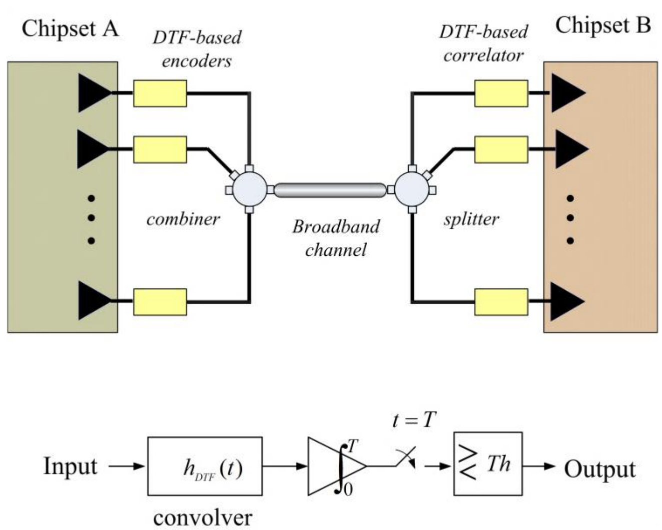

Fig. 2. (Upper) Conceptual diagram illustrating the application of the DTF (Bottom) CDMA receiver

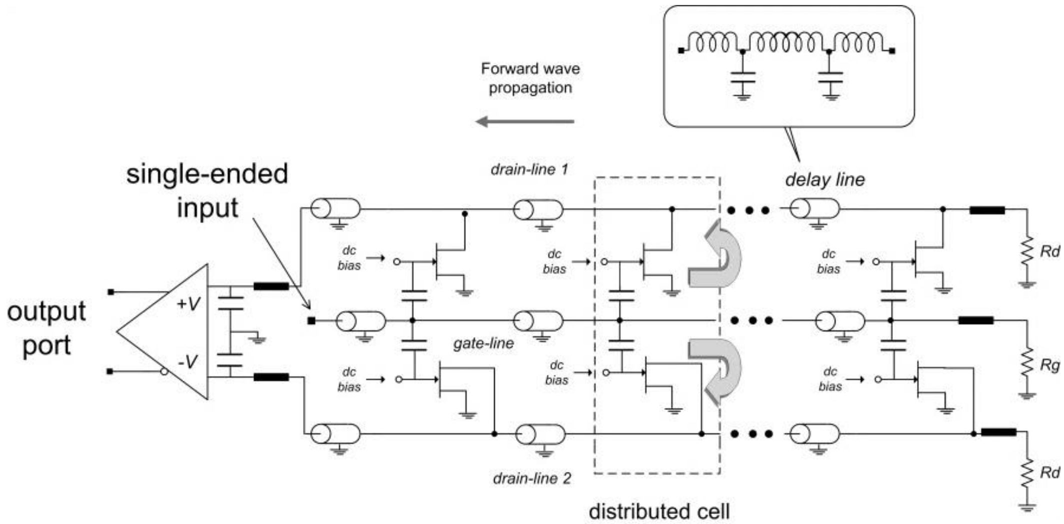

Fig. 3. Multi-GHz dual-drain line structure proposed for encoders and decoders

integrated filter stimulated by narrow input pulses are found in the next section, followed by the capabilities of DTFs for ST and DS coding and, finally, the correlation process is analyzed in the context of phase-addressing CDMA systems.

2 DTF Transient Responses

Microwave transversal filter for spread spectrum (SS) systems is designed by equalizing the time delay between filter stages to the chip interval so that a tapped pulse is amplified by a distributed gain proportional to a codeword element. We explore the capabilities of reconfigurable filters in which the phase of the gains and the tap gain weights are adjusted in correspondence to a multilevel CDMA signal.

The filter architecture is illustrated schematically in Fig. 3 and can be viewed as two distributed amplifiers sharing a common input line. The traveling wave structure was first proposed in [2, 6]. Here, we add a differential circuit at the output. Performance of such a distributed structure depends on the efficient wave propagation along drain lines and this was assessed using a methodology based on scattering parameters and fully characterized models of the HEMT (high electron mobility transistor) process [11]. Filter non-idealities such as impedance mismatch resulting from biasing devices at different voltage levels (which is necessary to achieve tap gain variation) and other wave phenomena do not compromise the filter transfer function. As input pulses travel down the gate line, distinct active coupling levels induce differential and common-mode waves propagating simultaneously along drain lines. Simulation results indicate that a differential circuit at the output port can cancel out common-mode waves with low performance degradation.

Each distributed cell consists of two HEMT's capacitively coupled to the gate line which allows independent voltage biasing in cell devices to set tap gain weights. The requirement of delay lines were diminished by taking traveling waves on drain lines in the counterpropagating direction, which renders a tap delay equal to additive delays in gate and drain-line stages [1]. Losses on the gate line associated to active devices increase phase linearity and induce frequency-dependent attenuation. The 3-dB point of the filter was set to a half of the (Bragg) cut-off frequency of the gate line to meet phase distortion and attenuation trade-off [2]. In order to set the tap delay between active cells equal to the chip interval impedance, matched *loss-free* delay lines were added between active cells as shown in Fig. 3. Such lines are constructed as inductance-capacitance (LC) ladders of metal-insulator-metal (MIM) discrete capacitors connected in shunt with high-impedance transmission lines. The dual drain line filter is less restricted by current handling capacity compared to single drain-line topologies enabling the design of delay line structures at higher frequencies and then smaller sizes. Two delay sections were needed on gate and drain lines to set an additive tap delay equal to 25 ps.

The filter processing can be described by the diagram in Fig. 4. It allows differentiating filter components that define pulse shape characteristics from those associated with pulse pattern generation.

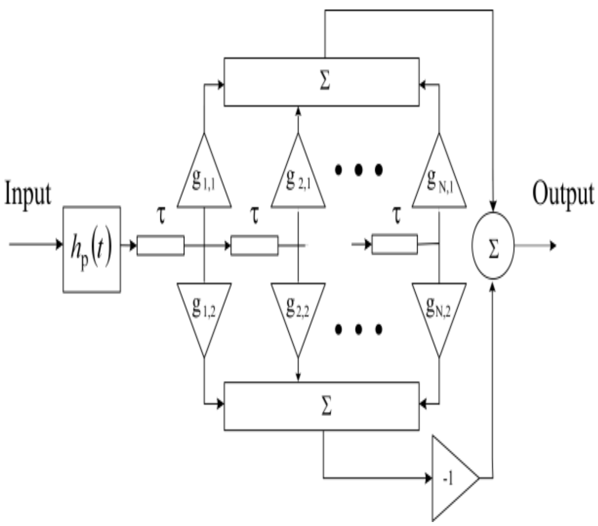

Fig. 4. Block diagram of the dual drain-line transversal filter designed with constant inter stage tap delay

The impulse transient function of such filter $h_{DTF}(t)$ is given by

$$h_{DTF}(t) = h_p(t) * \sum_{k=1}^{N} (g_{k,1} - g_{k,2}) \delta(t - k\tau) \quad (1)$$

where $h_p(t)$ is a factored out impulse function of all filter stages which describes the transient behavior associated to the filter bandwidth-limiting effects; $g_{k,1}$ *and* $g_{k,2}$ are the gain of the active devices at the amplifier stage k; τ is the delay time between taps; δ is the delta function and "*" denotes convolution operation.

Eq. 1 provides an approximated representation of the filter as a signal processor since the filter response to narrow pulses is a sequence of output pulses traveling at different inter-stage constant delays and with distinct transient characteristics. However, it provides a good description of the filter performance when used as a signal processor in the undertaken application. Fig. 5 shows simulation results using full parameters of an 8-tap DTF obtained by adjusting separately a given filter tap to the maximum gain and the remaining tap weights set to zero.

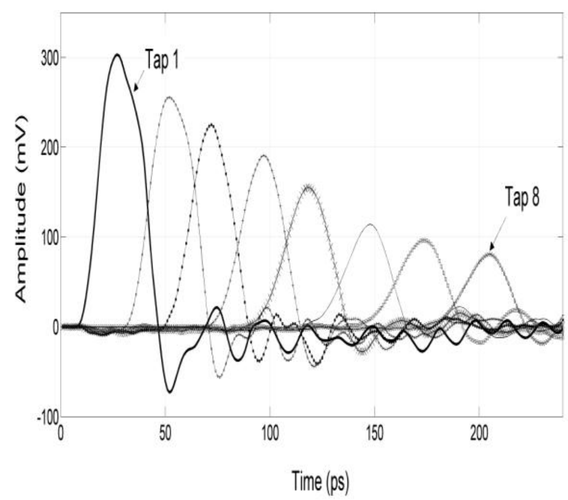

Fig. 5. Transient responses of the monolithic DTF to a single 25ps input pulse

The balance between code length and pulse shape integrity is set by the transient responses of the DTF. It is well known that for linear-phase wideband amplifiers, the step-response rise time $t_{r,n}$ is equal to the pulse width of the (nth-stage) impulse response. For DTFs, both parameters vary between filter stages due to the intrinsic bandwidth degradation of distributed circuits [10]. As a consequence, the width of pulses traveling at different filter paths will increase to such a level that tails interference from adjacent pulses. The criterion adopted for low inter-pulse interference establishes that all filter stages must present a rise time lower than the filter delay time τ which allows setting a filter function coefficient with low inter-pulse interference. Transient response analysis indicates that all filter stages satisfy such criterion. A practical limitation, however, which must be taken into consideration, is the high-frequency oscillatory components of all filter taps since these responses may add in phase according to the function to be implemented. For the coding methods employed herein, 8-tap DTF keeps low oscillation components in coding patterns. The reception of CDMA signals that present interference extending beyond the symbol interval does not imply necessarily data reception with ISI even though correlators present similar oscillatory responses [2, 10].

3 DTF Approach for DS-CDMA System Methods

As mentioned above, losses and bandwidth impairments limit the implementation to typically 8 taps leading to short spreading waveform implementations and thus low processing gain in the receivers. Consequently, data detection is quickly impaired as more users are added to the network. A method to improve system performance while increasing the number of sequences with good correlation properties consists in enabling time alignment of encoded signals, i.e., creating a synchronous CDMA network. By this means, the codes can be chosen for minimal interference.

In DS systems, the user transmits data bit '1' by sending the sequence assigned to the intended user in the time T ($T_{\text{chip}} = T/N$, N being the number of chips in the sequence) and transmits nothing for zero bit. When using distributed transversal filtering for encoding, the bearing information signal is an amplitude modulated pulse which is introduced at the filter input. The width of this pulse must be of the order of the chip interval. The input pulse is amplified by a gain proportional to the code element, and the encoder waveform $w(t)$ corresponds to the summation of N pulses:

$$w(t) = \sum_{k=1}^{N} a_k \, p_k(t) \tag{2}$$

where a_k is the kth-element of the sequence (normalized to a maximum device gain) and $p_k(t)$ is the filter pulse response of the kth-stage as shown in Fig. 5.

Despite the fact that these sequences are digital in nature, analog tap gain weight control is necessary to compensate for pulse concatenation and different attenuation levels introduced along filter paths. DS coding pattern generation using multi-Gb/s DTFs have been previously reported in [2-4]. Here, only the responses of the DTF as correlator are described. Fig. 6 displays typical responses of the DTF using Gold sequences of length 7. One intended transmitter with the signature sequence (–1,–1,+1,+1,+1,–1,–1) and one interferer with the sequence (–1,+1,–1,+1,–1,–1,–1) are applied to the DTF input.

Fig. 6 shows the correlator output (auto and crosscorrelation functions). It shows that the user pulse must be decoded at the chip interval to avoid large interference. A disadvantage in the use of Gold codes or other ±1 unbalanced codes (such as "positive" chip sequences in [3]), particularly when used in high-speed CDMA

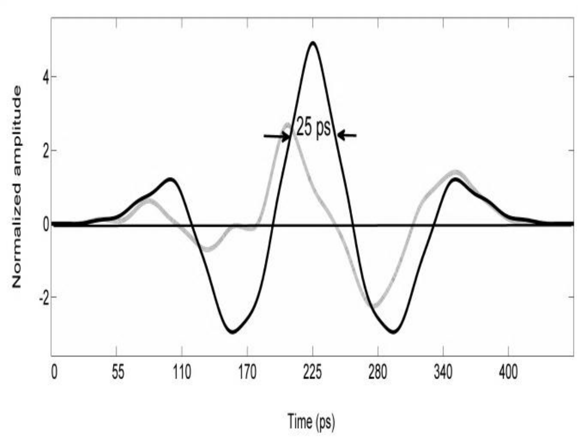

Fig. 6. Responses of the DTF as convolver, autocorrelation (black line) and cross-correlation (grey line)

systems, is the transmission of encoded signals with significant low-frequency content. This results in large multiple user interference when input buffers are designed with relatively large integration constants to match the despread user pulse. As mentioned earlier, a high-speed sampler that attains observation times of the chip interval leads to a costly implementation and therefore care must be paid on the spectral characteristics of encoding functions used. In the following section the spectral encoding is introduced as a technique that provides an advanced method for DTF-based CDMA networks.

4 Electrical Encoding and Correlation for ST Systems

In the following, we refer to a spread in time waveform as the time representation of a spectrally modulated signal whose phases of its constituent subbands are set according to a unique code. This spreading waveform is limited in time by the filter span, i.e., the total delay time on the tapped line. A representation for the filter waveform $w(t)$ that suits the characteristics of the DTF is given as a summation of M sinusoids:

$$w(t) = p(t)\sum_{n=1}^{M}\cos(2\pi nt/T + \varphi_n) \quad (3)$$

where T is the symbol interval equal to the DTF's time span, φ_n is the initial phase of the nth-component and $p(t)$ is a gate function that truncates the modulated sinusoids by a symbol interval. Signal generation based on the modulation of components as in Eq. 3 needs a rather complex analog processing and its synthesis is usually achieved using a discrete-time filter. Through simulations, it is shown here that the DTF does lend itself to a method for spectral encoding.

Spread-in-time waveform generation having its subbands spaced at the reciprocal of the symbol interval requires a spectral processing of the CDMA signals. The procedure to implement the waveforms by impressing codes on the phases of the subbands is shown in Fig. 7. The spreading waveform is defined by modulating in phase a multi-tone input signal according with a pseudonoise (PN) sequence which is related to the phases by the complex exponentials $\exp(j\varphi_n)$, $n = \{1,2,\ldots,M\}$. Since the waveform is real-valuated, $PN(f) = PN^*(-f)$ and the waveform is defined by a pseudonoise code of length M [9].

In the process to implement an impulse response, the filter responses are adjusted to values proportional to the analog samples of the ST signal. The waveforms are sampled with a number of filter taps that avoids aliasing the signal spectrum. As an approximation, if $p(t)$ is an ideal time-limiting window, the waveform spectrum consists of sinc(fT)-shaped subbands each separated by 1/T Hz. Under this assumption, it is straightforward to demonstrate that for a waveform given by Eq. 3, a sampling rate f_s equal to $2(M + 1)/T$ will not induce aliasing at discrete frequencies. Then the minimal number of samples which provides a non-aliased version of the analog waveform is set to be equal to the number of filter taps N. Since $T = N\tau$ and $f_s = 1/\tau$; one arrives at $N = 2M + 2$. Such number of taps ensures that the waveform conveys the correct phases defined by the codes, as verified by Discrete Fourier Transform techniques.

Given the limited responses associated with the distinct transient characteristics and bandwidth limitations, performance is investigated by tweaking the sampling time to approximate the DTF's response to the analog waveform over the available time span. For such aim, filter tap gain weights $g(n)$, $n = 1, \ldots, N$, are computed using the relationship presented in Eq. 4

$$g(k+1) = \sum_{n=1}^{M}\cos(2\pi n(k+\alpha)/N - \varphi_n) \quad (4)$$

where $k = 0,\ldots, N-1$ and α is a parameter chosen as a fraction of the pulse interval ($0 \le \alpha < 1$) to improve the approximation. Fig. 8 displays the generation of a spread in time waveforms and corresponds to the responses of 8-tap DTF with tap weights computed by Eq. 4. Signals are normalized with their rms values to equalize the transmitted power of each user in the network. The figure allows contrasting with the computed

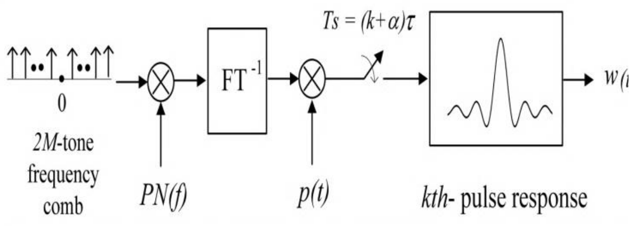

Fig. 7. Procedure for spread-in-time waveform implementation, where
FT $^{-1}$ = inverse Fourier transform

analog waveform, clearly showing time and amplitude mismatch; it also shows interference extending beyond the symbol interval.

Choice of codes for ST-CDMA systems can be made by considering the analytical expression of the correlation between two spread in time waveforms given by Eq. 3. The correlator output signal corresponds to a summation of terms that result from convolving sinusoidal components with equal frequencies and mixed terms by convolving components with different frequencies. As the correlation lag approaches to zero, the signals tend to be aligned to the initial phases defined by code, and the convolution between components with the same frequency gives rise to a decoded pulse whose amplitude is determined by code words. For K simultaneous users, zero

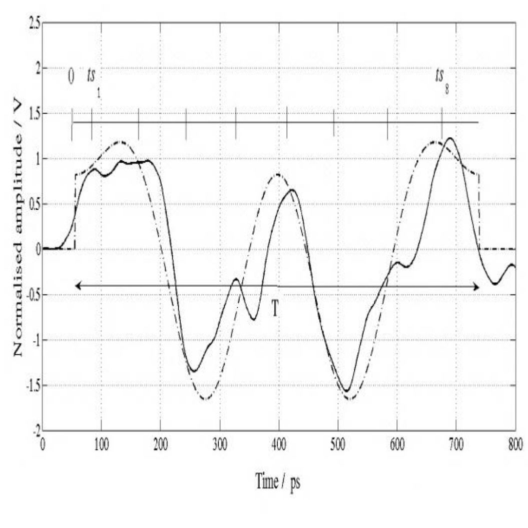

Fig. 8. Spread in time waveform with codeword [0, 0, π] and α = 0.25 (black line). The ideal (analytical) waveform is in dotted line

lag correlation $z_y(T)$ is given by Eq. 5.

$$z_y(T) = \sum_{x=1}^{K} \sum_{q=1}^{M} \cos\left(\varphi_{q,x} - \varphi_{q,y}\right) \qquad (5)$$

where $\varphi_{q,x}$ is the phase assigned to subband q of the user x and $\varphi_{q,y}$ is the corresponding phase of the receiver.

Code match from a desired transmitter and correlative interference from unwanted transmitters produce the output given by Eq. 5. However, crosstalk between users can be made equal to zero by using sequence elements chosen from a set of uniformly spaced points on the unit circle, such as 0, π/2,–π/2 and π.

At other correlation lags, the interference is despread in the form of a high frequency signal which in turn is lowpass filtered by the input buffer and successive stages. Therefore, the frequency slots of the encoding waveforms will always be aligned and the receiver output depends only on the code phases as given by Eq. 5.

By using codes that allow complete crosstalk rejection as those proposed in [12], a direct application to CDMA system can be realized taking into account the correlation function achieved by the electrical transversal filtering.

Codes that satisfy perfect periodic correlation have been proposed for CDMA networks [12]. Let us consider the shift-and-add property of maximal-length (M) code of order 3, (1 1 –1) and its reciprocal (1 1 0) [13]. Table 1 shows the periodic correlation and the computed correlator output.

The correlation is different from zero for codes in column 1, while shifting code as indicated in columns 2 and 3 gives a zero correlation output. Theoretically, multiple-access interference can be completely rejected.

In order to compute the correlation function by transversal filtering, we assign a code element ‘1’ to 0 radian phase, which leads to assign ‘–1’ to π radian and ‘0’ to π/2 radian phases on the unit circle. It is worth mentioning that this choice is arbitrary and a phase-shift in all the code phases could be applied without modifying the correlation function. This phase-shifting invariance is important to be considered given that the choice

Table 1. Periodic correlation of *M*-code with its reciprocal

Codes	Shift and add 1	Shift and add 2
+1 +1 −1	+1 +1 −1	+1 +1 −1
1 1 0	0 1 1	1 0 1
$1{\times}1{+}1{\times}1{-}1{\times}0 = 2$	$1{\times}0{+}1{\times}1{-}1{\times}1 = 0$	$1{\times}1{+}1{\times}0{-}1{\times}1 = 0$

of code elements might result in improved waveform approximations.

Codes in column 1, (+1 +1 −1) and (1 1 0), are equivalent for the "spectral" encoding to the codes (0, 0, π) and (0, 0, π/2), respectively. After shifting the unipolar codes, (π/2, 0, 0) and (0, π/2, 0) are orthogonal to the receiver code (0, 0, π). Results based on full layout simulation and using the codes above are as follows.

Fig. 9 shows the correlation output to 3 simultaneous users. Only '1' bit pulses are code modulated. It is seen that correlative interference takes a low positive value at the sampling time *T* and increases greatly at other lag times. The low correlative interference at the sampling point indicates good accuracy on the waveform generation and correlation functions.

Fig. 10 shows the effect of passing the correlation output signal through a lowpass filter, which was designed as a second order Butterworth filter with a cut-off frequency of 5 GHz. An amplifier between the filter structure and the lowpass filter was included in order to ensure broadband summation of encoded signals prior filtering. Results of the ideal (theoretical)

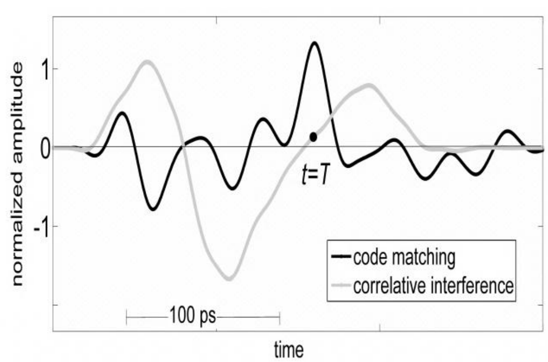

Fig. 9. Correlative response of the receiver with code (0, 0, π) to 3 simulataneous users

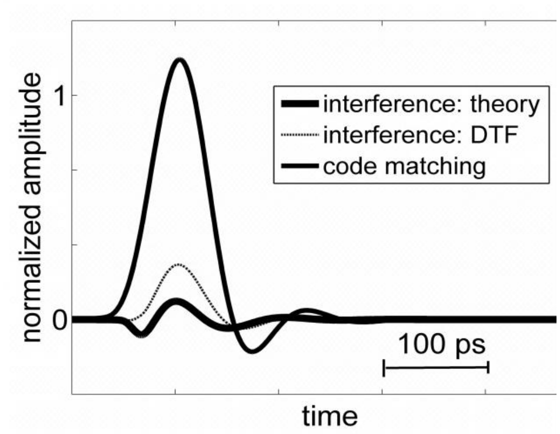

Fig. 10. Pulse and interference after lowpass filtering

waveform are included to make comparisons with responses obtained by the DTF. In principle, the interference cannot be equal to zero given the filter inaccuracies and also due to the fact that the spectra of the available subbands extend into neighbor frequency bands, which prevents creating perfectly orthogonal channels.

Note that for the analytical waveforms, the broaden spectra of the subbands induce low interference at the output of the lowpass filter, however, it results to be lower than the despread user pulse. The capability of detecting encoded waveforms at lower frequencies allows subsequent detection circuits to work at a bit-rate speed.

6 Conclusions

This article introduces an advanced method based on distributed transversal filtering for spectrally coded CDMA systems. It was shown that by adopting simple changes on the method to set tap gain settings, the DTF is a prospective component to achieve encoding and decoding functions for phase-addressing CDMA networks. The filter responses provide an approximation to short spreading waveforms over a given time span while, when used as a correlator, the DTF programmed with a multilevel code can achieve desired correlation properties. The coding method would allow 3 simultaneous users to share the available channel. Ongoing work is in the capability to encode data onto multi-phase encoding waveforms. This entails a careful choice of codes and filter structures that allow increasing the number of codes with good correlation properties. Circuit design based on optimization techniques will be a key point to be explored with the aim to construct optimized encoders and decoders for spectrally efficient CDMA systems.

References

1. **Borjak, A., Monteiro, P.P., O'Reilly, J.J., & Darwazeh, I. (1997).** High-Speed Generalized Distributed-Amplifier-Based Transversal-Filter Topology for Optical Communication Systems. *IEEE Transactions on Microwave Theory and Techniques*, 45(8), 1453–1457.
2. **Aguilar-Torrentera, J. & Darwazeh, I. (2005).** Dual drain-line distributed cell design for multi-Gbit/s transversal filter implementations. *IEEE International Symposium on Circuits and Systems (ISCAS 2005)*, Kobe, Japan, 4, 3958–3961.
3. **Pimenta, M.N. & Darwazeh, I. (2006).** Novel Encoder and Correlator for Optical Code Division Multiple Access Networks. *19th Annual Meeting of the IEEE Lasers and Electro-Optics Society (LEOS 2006),* Montreal, Canada, 422–423.
4. **Rosas-Fernandez, J.B., Ingham, J.D., Penty, R.V., & White, I.H. (2009).** 18 Gchip/s Electronic CDMA for Low-Cost Optical Access Networks. *Journal of Lightwave Technology*, 27(3), 306–313.
5. **Lam, C.F. (2000).** To Spread or Not to Spread: the Myths of Optical CDMA. *13th Annual Meeting of the IEEE Lasers and Electro-Optics Society (LEOS 2000)*, Rio Grande, Puerto Rico, 2, 810–811.
6. **Aguilar-Torrentera, J. & Darwazeh, I. (2004).** Distributed Amplifier Based MMIC for Multi Gb/s Optical CDMA Systems. *9th European Conference on Networks & Optical Communications*, Eindhoven, The Netherlands, 164-169.
7. **Zahedi, S. & Salehi, J.A. (2000).** Analytical Comparisons of Various Fiber-Optic CDMA Receiver Structures. *Journal of Lightwave Technology*, 18(12,) 1718-–727.
8. **Salehi, J.A., Weiner, A.M., & Heritage, J.P. (1990).** Coherent Ultrashort Light Pulse Code-Division Multiple Access Communication Systems. *Journal of Lightwave Technology*, 8(3), 478–491.
9. **Crespo, P.M., Honig M.L., & Salehi, J.A. (1995).** Spread-Time Code-Division Multiple Access. *IEEE Transactions on Communications*, 43(6), 2139–2148.
10. **Aguilar, J. (2005).** Transversal Filter MMIC Design for Multi-Gbit/s Optical CDMA Systems, Ph. D Thesis Abstract. *Computación y Sistemas*, 8(4), 334–342.
11. **Aguilar-Torrentera, J. & Darwazeh, I. (2007).** Performance Analysis of a Monolithic Integrated Transversal Filter Using Mixed-Mode Scattering Parameters. *IET Microwaves, Antennas and Propagation*, 1(4), 925–931.
12. **Kavehrad, M. & Zaccarin, D. (1995).** Optical Code-Division-Multiplexed Systems Based on Spectral Encoding of Noncoherent Sources. *Journal of Lightwave Technology*, 13(3), 534–545.
13. **Fan, P. and Darnell, M.** "Sequence Design for Communication Applications", *Research Studies Press*, John Wiley&Sons, 1996 *http://www.amazon.com/Communications Applications-Techniques-Electronic Engineering/dp/086380201X*

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