NONCOHERENT UWB IMPULSE RADIO AND FM-DCSK: WHAT MAKES THEM DIFFERENT

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Abstract— *For lack of empty radio bands, ultra-wideband (UWB) radio system allowing reuse of already occupied frequency bands is the only solution to accommodate new wireless data communication services. Two types of UWB carriers are considered here, the frequency-shifted Gaussian pulse and chaotic signal with FM-DCSK modulation.*

A generalized model of transmitted reference systems is introduced first that makes the comparison of noncoherent UWB impulse radio and chaotic FM-DCSK system possible. The noise and interference rejection capability of a detector depends on the amount of a priori *information exploited. In indoor radio applications the autocorrelation receiver is preferred since it provides the best robustness against the channel distortions. The paper shows that the autocorrelation receiver exploits only a limited part of* a priori *information, consequently, the noise performances of noncoherent UWB impulse radio and FM-DCSK are identical. Finally, the feasibility of noncoherent UWB impulse radio and chaotic FM-DCSK is verified. It is shown that UWB radios may be built by chaotic carriers and that UWB application offers a new research field for the chaotic research community.*

I. Introduction

There is a huge market demand for wireless data communications, everything from computer keyboard to sensor networks is expected to operate wireless. Unfortunately, the frequency bands available for radio communications are already occupied and there are no empty frequency bands especially in that region where CMOS technology may be used. The only solution is the reuse of frequency bands occupied already. This can be done if the transmitted signal is spread over an extremely wide frequency band and the power spectral density (psd) of transmitted signal is low enough not to cause noticeable interference in the existing conventional narrowband communication systems.

The other issue why a wideband carrier has to be used is the multipath propagation since this is the phenomenon that limits the coverage of radio communications in indoor and mobile applications.

Both problems may be overcome if an extremely wideband signal is used to carry the digital information. However, there is a significant difference between the conventional spread spectrum (SS) system and ultra-wideband (UWB) radio. In the former, the bandwidth is large compared to the *data rate* but the RF bandwidth is still small compared to the carrier frequency. In UWB radio, the RF bandwidth is large even compared to the *center frequency* of radiated signal.

An extremely wide frequency band has been allocated for the UWB radio, it extends from 3.1 GHz up to 10.6 GHz [1]. The generation and reception of such a wideband signal with CMOS technology featuring an extremely low power consumption are very hard tasks that cannot be solved using the conventional linear approaches. The nonlinear research community should take up this new challenge that will open new research fields.

The frequency band allocated to UWB radio is not empty, many conventional narrowband systems have been operating in that frequency band. To mitigate interference, the power radiated in a 1-MHz bandwidth is limited as shown in Fig. 1 by the emission mask proposed for indoor UWB systems by the European Technical Standards Institute (ESTI). Note, the mask allows to transmit -41.3 dBm in a 1-MHz wide frequency slot. The radiated signal must be a wideband signal, the bandwidth of transmitted UWB signal must exceed 500 MHz. The required data rates are 1 kbps, 10 kbps and 1 Mbps. The typical distance between the transmitter and receiver is 30 m and the transceiver including sensor and data processing layers are expected to operate for years without changing the battery.

The psd of radiated signal allowed by the emission mask is extremely low. Unfortunately, the coverage of a radio transmission depends mostly on the transmitted power. To increase the transmitted power, an extremely wideband carrier is required as done in UWB radio where a frequency-shifted Gaussian pulse [1] or chaotic signals [2] are used to carry the information. However, the ultra-wideband signals have no amplitude, phase and frequency in the conventional sense.

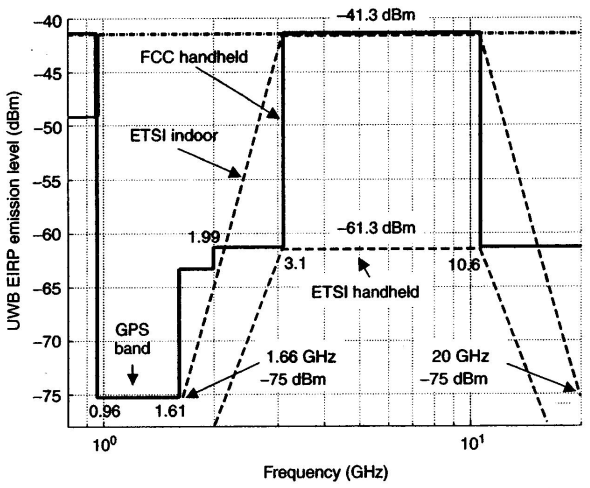

Fig. 1. Emission mask for handheld and indoor UWB systems proposed by the European Technical Standards Institute (ESTI).

This is why novel modulation schemes had to be elaborated.

To get a low-cost transceiver, noncoherent modulation schemes such as (i) chaotic on-off keying (COOK) [3], (ii) direct chaotic communication (DCC) with OOK [4], (iii) chaotic frequency-modulated differential chaos shift keying (FM-DCSK) [5] and (iv) noncoherent impulse radio [1] have been proposed.

Although the performance of chaotic systems may be improved by increasing their complexity [7], only the simplest chaotic modulation scheme is considered here in order to get the lowest power consumption.

Among the modulation schemes proposed for UWB hitherto, the noncoherent impulse radio and FM-DCSK modulation offer the most robust and simplest receiver configuration. This paper compares and checks the feasibility of these modulation schemes. To provide a unified framework for the comparison, the idea of generalized transmitted reference (TR) system is introduced. It is shown that both modulation schemes belong to the family of TR systems, the only difference between noncoherent UWB impulse radio and FM-DCSK is that in the former a deterministic signal, while in the later a continuously varying chaotic signal is used as carrier. The application of the Fourier analyzer concept to the generalized TR model shows that in case of a deterministic carrier more *a priory* information is available to construct an optimum detector. However, if an *autocorrelation receiver* configuration is used in order to get a robust but very simple receiver configuration then only a part of *a priori* information is exploited and in this case it is enough to keep the transmitted energy per bit constant to achieve the optimum noise performance. It can be also done for the chaotic carriers, if so then the noise performances of chaotic and impulse radio systems are identical.

To make FM-DCSK less sensitive to multipath propagation, a novel FM-DCSK modulation scheme is proposed. Finally the paper verifies the feasibility of UWB FM-DCSK and noncoherent impulse radio systems.

II. Transmitted Reference Systems

A. Generalized model for TR modulation

In a binary TR system two signals, called chips, are used to transmit one bit information. The first chip serves as a reference, while the second one carries the information.

The structure of a generalized TR signal is shown in Fig. 2, where $g(t)$ denotes an arbitrary carrier wavelet, τ is the chip duration and $\Delta T \geq \tau$ gives the delay between the two chips. The best noise performance is achieved by the antipodal modulation scheme where the information bearing chip is equal to the delayed reference chip for bit "1," and to the inverted and delayed reference chip for bit "0."

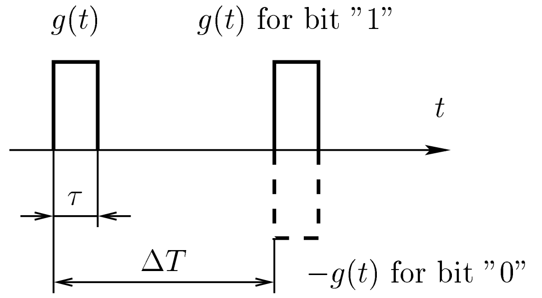

Fig. 2. Structure of generalized TR signal.

The unique feature of a TR radio system is that the reference chip is not recovered at the receiver but it is transmitted via the same telecommunication channel as the information bearing chip. This solution makes the TR radio system very robust against the linear and nonlinear channel distortions, but it has a serious drawback: both the reference and information bearing chips are corrupted by the channel noise. As shown later, the noisy reference chip results in a noise performance degradation.

The fact that the reference chip is transmitted via the same telecommunication channel is generally considered as a disadvantage, since it is considered only as a loss in transmitted energy per bit. This statement is valid only if a distortion free channel, where the received signal is corrupted by a white Gaussian noise in an additive manner, is considered. However, the real channels always have distortion, either linear or nonlinear. In case of channel distortion, the information bearing chip has to be correlated with a reference one distorted in the same manner as the information bearing chip to get the best system performance. A correlation with the original distortion-free reference results in a performance degradation. Since in a TR system both the reference and information bearing chips undergo the same distortion, the TR system offers a better system performance when distortion is present in the channel, provided that the loss caused by the noisy reference chip is less than the gain arising due to the perfect correlation of the reference and information bearing chips. The reference chip should be considered as a test signal used to measure the actual channel characteristics. Consequently, the TR system may be used even in a time-varying channel.

Note that the generalized model shown in Fig. 2 gives the transmitted signal both for noncoherent impulse radio [1] and for FM-DCSK [5].

B. Noncoherent Impulse Radio System

A fixed waveform, namely an impulse is used as carrier $g(t)$ in the noncoherent impulse radio system. Because of its bandpass property, a frequency-shifted Gaussian pulse is used as $g(t)$ in noncoherent UWB impulse radio.

C. Generalized FM-DCSK Technique

Although in the original version of FM-DCSK the chip duration τ and delay ΔT are identical, the reference and information bearing chips may be separated $\Delta T > \tau$ to prevent intersymbol interference (ISI) in UWB application. The former assures the maximum data rate while the latter prevents the intersymbol interference caused by the multipath channel.

D. TR autocorrelation receiver

Due to the special structure of TR signal, the information bits may be recovered from the sign of correlation measured between the reference and information bearing chips as shown in Fig. 3. The channel filter is a bandpass filter that determines the noise bandwidth of receiver. The integrator is a integrate-and-dump circuit. In consequence of the antipodal modulation scheme, the optimum decision threshold is always zero independently of the signal-to-noise ratio (SNR) measured at the demodulator input [5].

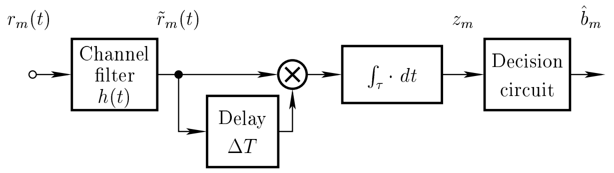

Fig. 3. Block diagram of TR autocorrelation receiver.

III. Noise performance of TR Systems

Both noncoherent UWB impulse radio and FM-DCSK systems belong to the TR systems, but in the former a fixed waveform while in the latter a chaotic carrier is used as $g(t)$. The advantages of these TR systems are: (i) the optimum decision threshold is always zero, consequently, there is no need for an adaptive threshold control and training sequence, (ii) the reference chip measures the actual channel characteristics, (iii) a simple autocorrelation receiver may be used.

The TR systems also have a few disadvantages: (i) transmission of a reference chip results in a loss in the energy per bit E_b (however, this loss may be reduced if more than one information bearing chips are transmitted after one reference chip), (ii) the reference chip is also corrupted by the channel noise.

The Fourier analyzer concept introduced in [8] gives an exact mathematical model for the detection problem. It defines a Hilbert space in which all received signals, either deterministic or random, can be expressed. Using the *a priori* information available at the receiver, subspaces for both bits are constructed and the detector observes these subspaces. The noise and interference rejection capability of a detector depends on the amount of *a priori* information: the more the *a priori* information, the better the noise performance. This is why the best noise performance may be achieved by a deterministic carrier.

However, in many applications only a limited amount of *a priori* information is exploited in order to get a more robust or simpler detector configuration. Due to the special structure of TR signals the elements of signal set are always separated in the frequency domain regardless of the type of carrier $g(t)$. The spectrum of bits “1” and “0” contain only the even and odd harmonics, respectively, of the bit duration T [9]. In an autocorrelation receiver only this limited amount of *a priori* information is exploited.

If only this separation in the frequency domain is exploited during the detector construction then only one condition has to be satisfied to achieve the best noise performance, namely, the transmitted energy per bit has to be kept constant [10]. This condition is always met in case of fixed waveform communications, but is not automatically satisfied in chaotic communications where the carrier $g(t)$ varies from bit to bit even if the same bit is transmitted repeatedly. In chaotic communications an extra signal manipulation, for example the frequency modulation in FM-DCSK, is required to generate a carrier with constant E_b.

The equation developed in [10] for noise performance may be generalized to any kind of TR systems implemented with an autocorrelation receiver. The bit error rate (BER) is obtained as

$$\begin{aligned} P_e = &\frac{1}{2^{2B\tau}} \exp\left(-\frac{E_b}{2N_0}\right) \sum_{i=0}^{2B\tau-1} \frac{\left(\frac{E_b}{2N_0}\right)^i}{i!} \\ &\times \sum_{j=i}^{2B\tau-1} \frac{1}{2^j} \binom{j+2B\tau-1}{j-i} \end{aligned} \qquad (1)$$

where $N_0/2$ denotes two-sided psd of channel noise. This equation is valid for both fixed and chaotic carriers provided that the energy per bit E_b is kept constant.

In Equation (1), τ denotes the energy capture time of autocorrelation receiver. In a well designed system the chip duration is equal to the capture time, this is why these parameters are not distinguished in Fig. 2 and in (1). Note that the noise performance of a TR system depends on the product of $2B\tau$, but the delay $\Delta T - \tau \geq 0$ between the reference and information bearing chips has no influence on the noise performance. The dependence on $2B\tau$ reflects the fact that both the reference and information bearing chips are corrupted by the channel noise.

IV. Feasibility of a TR UWB Radio

Let us check the feasibility of a TR UWB system where the bandwidth of transmitted signal is 500 MHz. According to the ESTI regulation shown in Fig. 1 the radiated power is as low as -14.3 dBm. The carrier $g(t)$ may be either a chaotic signal or a frequency-shifted Gaussian pulse. The only free parameter is the bit duration, its effect on noise performance has to be determined.

For simplicity, assume that $\Delta T = \tau$, i.e., the bit duration is $T = 2\tau$. Recall that the insertion of a guard time between the reference and information bearing chips, $\Delta T > \tau$, does not change the noise performance of the TR UWB system.

Let the noise figure NF of the implemented receiver be 3.5 dB and consider the bit durations of 200, 400 and 600 ns. Typical parameters of the UWB radio systems are:

FCC emission limit:	-41.3 dBm/MHz
Bandwidth of channel filter:	$2B = 500$ MHz
Radiated power:	$P = -14.3$ dBm
Center frequency:	4 GHz
Path loss (about 30 m):	74 dB
Implementation loss:	1 dB

The maximum coverage of radio communications is shown in Fig. 4, where the BER is plotted against the distance measured between the transmitter and receiver, and where the parameter is the bit duration. As expected, the longer the bit duration, the longer the distance over which the communications may be established.

Figure 4 shows that the TR UWB radio is feasible since if the receiver noise figure is 3.5 dB and the bit duration is 400 ns then the coverage range is about 25 m. The coverage may be increased by increasing the radiated power. Since the psd is limited it can be done by increasing the bandwidth of transmitted signal.

V. Conclusion

Since the frequency bands suitable for data communication with CMOS technology are already occupied, the frequency reuse, i.e., the UWB radio offers the only solution for accommodating new data communication channels. In the deterministic UWB approach a frequency-shifted Gaussian pulse with a duration of about 1 ns is used as carrier. However, the generation of such a narrow pulse with CMOS is a very hard task and the transmission such a signal requires a linear transceiver that has a large power consumption.

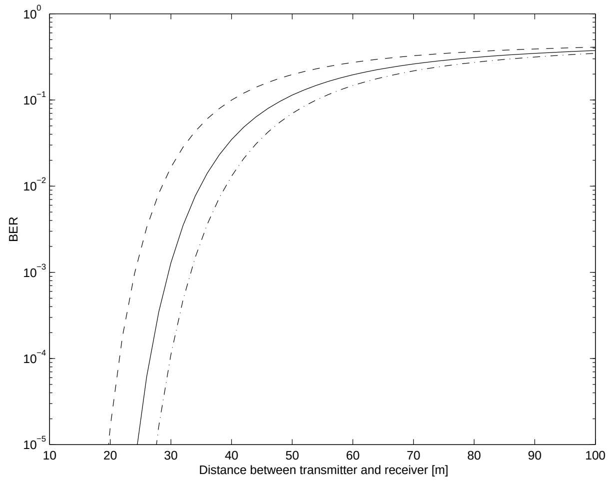

Fig. 4. Noise performance of a UWB FM-DCSK system as a function of distance measured between the transmitter and receiver for different bit durations: $T = 200$ ns (dashed curve), $T = 400$ ns (solid curve) and $T = 600$ ns (dash-dotted curve).

Chaotic communications offers an alternative solution to UWB radio. Since an extremely wideband signal must be used as UWB carrier, this application really exploits the inherent wideband property of chaotic signals that may be generated by very simple circuitry. This paper has shown that (i) both chaotic FM-DCSK and noncoherent UWB impulse radio belong to the same class of modulation scheme, consequently, they have the same system performance, and that (ii) the chaotic UWB radio is feasible.

References

[1] K. Siwiak and D. McKeown. *Ultra-Wideband Radio Technology.* Wiley, Chichester, UK, 2004.

[2] L. M. Pecora and T. L. Carroll. Synchronization in chaotic systems. *Phys. Rev. Letters*, 64(8):821—824, 1990.

[3] M. P. Kennedy and G. Kolumbán. Digital communications using chaos. In G. Chen, editor, *Controlling Chaos and Bifurcations in Engineering Systems*, chapter 22, pages 477–500. CRC Press LLC, Florida, 1999.

[4] Yu. V. Andreyev, A. S. Dmitriev, E. V. Efremova, A. D. Khilinsky, and L. V. Kuzmin. Qualitative theory of dynamical systems, chaos and contemporary wireless communications. *Int. Journal of Bifurcation and Chaos*, 15(11):3639–3651, November 2005.

[5] G. Kolumbán, M. P. Kennedy, and G. Kis. Performance improvement of chaotic communications systems. In *Proc. ECCTD'97*, pages 284–289, Budapest, Hungary, August 30–September 3, 1997.

[6] A. F. Molisch *et. al.* Impulse Radio. January 18, 2005. IEEE 802 Online Document: <http://grouper.ieee.org/groups/802/15/pub/05/>.

[7] M. Hasler and T. Schimming. Optimal and suboptimal chaos receivers. *Proceedings of the IEEE*, 90(5):733–746, May 2002.

[8] G. Kolumbán, F. C. M. Lau, and C. K. Tse. Generalization of waveform communications: The Fourier analyzer approach. *Circuits, Systems and Signal Processing*, 24(5):451–474, September/October 2005.

[9] G. Kolumbán. A new frequency-domain FM-DCSK detector. In *Proc. ECCTD'03*, Kraków, Poland, September 1-4, 2003.

[10] G. Kolumbán. Theoretical noise performance of correlator-based chaotic communications schemes. *IEEE Trans. Circuits and Syst. I*, 47(12):1692–1701, December 2000.