LR-WPAN and UWB data communication systems: A new possible application for chaotic carriers

(Invited Paper)

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***Abstract*—Radio communications via channels already occupied by conventional telecommunication systems can be established only by Ultra-WideBand (UWB) radio where the spectrum of transmitted signal covers an ultra-wide frequency band. The power spectral density (psd) of transmitted UWB signal is extremely low and does not cause any noticeable interference in the conventional telecommunication systems. The paper compares the chaos-based and UWB impulse radio systems and shows that chaotic carriers can be used for the implementation of UWB radio.**

I. INTRODUCTION

Chaotic signals are ultra-wideband signals that can be generated with simple circuits in any frequency bands at arbitrary power level. The ultra-wideband property of chaotic carriers is beneficial in indoor and mobile applications where multipath propagation limits the attainable Bit Error Rate (BER). To exploit this feature of chaotic carriers, chaos-based digital communication schemes have been developed. Unfortunately, the Quality of Service (QoS) achieved by chaos-based systems lags behind that of the conventional ones when high data rate and a high BER are required.

Until this time the research efforts have focused on the search for an optimum chaos-based modulation scheme, while the channel conditions and application requirements have not been considered. However, the correct way to find applications for chaos-based communications is that first the theoretical performance limit of chaos-based communications and the reasons which limit the system performance have to be identified. Then those applications have to be collected where the disadvantages of chaotic carriers are irrelevant or negligible. Recall, the types of carrier and modulation scheme should be always matched to the channel conditions and application requirements.

To find an adequate application for chaotic carriers first this paper surveys the theoretical performance bounds of chaos-based communication systems, then discusses the application requirements of sensor networks and embedded systems, two possible applications for chaos-based communications. Finally, the BER performance of the impulse radio, a conventional solution to UWB radio, and chaos-based communication systems are compared.

II. THEORETICAL PERFORMANCE BOUND OF CHAOS-BASED COMMUNICATION

In the literature, the type of circuit generating the carrier is used to classify the data communication systems. According to this conventional approach we distinguish sinusoidal-based, chaos-based and noise-based systems.

However, if the theoretically attainable BER is considered then the conventional approach cannot be used. Instead, a signal processing approach has to be used where two types of carriers are distinguished: communication with (i) fixed or (ii) continuously varying waveforms [1].

In the first approach, each symbol is mapped into a unique and fixed waveform. The transmission of identical symbols results in the transmission of a series of identical waveforms. Therefore, this approach is referred to as communication with fixed waveforms. The method of generation of waveforms is irrelevant, the carrier can be a deterministic signal or a windowed chaotic signal stored in a memory.

In the second version of waveform communications the carrier is the actual output of a chaotic signal generator, consequently, it is a continuously varying waveform. Even if the same symbol is transmitted repeatedly, different chaotic waveforms are radiated. This paper is devoted to this approach which is referred to as chaos-based communications.

In digital communications, the elements of signal set carrying the different symbols pass through the radio channel in which they are corrupted by noise, may suffer from distortion, interference and multipath. Observing the corrupted and distorted received waveform for the interval of symbol duration, the detector decides which message has most likely been transmitted. The *a priori* information, i.e., the knowledge of signal set is exploited by the detection algorithm to suppress channel noise and interference. A rule of thumb: the less the *a priori* information exploited, the worse the BER. To get the theoretically attainable noise and interference suppression capability of a chaos-based system, the maximum amount of attainable *a priori* information has to be determined.

A. Block diagram of a receiver

The general block diagram of a digital waveform communication receiver is shown in Fig. 1. The transmitted signal

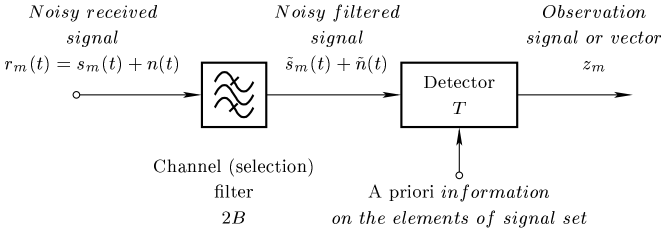

Fig. 1. General block diagram of a digital waveform communication receiver.

$s_m(t)$ is corrupted by $n(t)$ that may be either a white Gaussian channel noise or an interference. To select the signal to be received, $r_m(t) = s_m(t)+n(t)$ is fed into a bandpass channel filter of RF bandwidth $2B$. The observation time period and channel filter bandwidth are identical to the symbol duration and bandwidth of transmitted signal, respectively.

The detector observes the filtered received signal $\tilde{s}_m(t) + \tilde{n}(t)$ over the symbol duration T and generates the observation variable z_m; it may be either a random scalar number or a random vector. The decision time instants, the symbol duration T and the RF bandwidth $2B$ of transmitted signal $s_m(t)$ are always known at the receiver.

B. Exact model of detection: The Fourier analyzer concept

The study of detection process requires the definition of a *received signal space* in which each signal, either deterministic or random, arising from channel filter may be exactly represented over the observation time period. To get the simplest model, a discrete and finite-dimensional signal space must be constructed.

In the *Fourier analyzer concept* [1] a Hilbert space spanned by the harmonically related $\cos(\cdot)$ and $\sin(\cdot)$ functions is used to construct the received signal space, the inner product of two functions is defined as their cross-correlation evaluated over the observation time and the norm of a signal is the square root of its energy received during the observation time period.

To get a discrete Hilbert space, a periodic signal must be constructed from the received noisy and filtered signal $\tilde{r}_m(t) = \tilde{s}_m(t)+\tilde{n}(t)$. Since the detector observes the received signal only over the symbol duration, from the detection point of view a periodic signal of period T may be constructed using

$$\tilde{r}_{T,m}(t) = \begin{cases} \tilde{r}_m(t), & \text{for } 0 \le t < T \\ \tilde{r}_m(t - CT), & \text{otherwise} \end{cases} \tag{1}$$

where C is an arbitrary nonzero integer. Note that the approximation introduced by (1) does not cause any distortion from the detection point of view as the periodic signal $\tilde{r}_{T,m}(t)$ coincides with waveform $\tilde{r}_m(t)$ on the interval $0 \le t < T$ where the detector observes the signal.

The dimension of received signal space has to be determined next. Figure 1 shows that the waveform observed by the detector is a bandpass signal, consequently, the periodic signal defined by (1) is also a bandpass signal.

By definition, the signal dimension gives the number of harmonically related $\sin(\cdot)$ and $\cos(\cdot)$ functions along which the receiver collects information on the received signal. In other words, the signal dimension gives the dimension of Hilbert space which is required to represent *any signal* appearing at the detector input *over the observation time interval*. The signal dimension is obtained as [1]

$$S_D = 4BT\,. \tag{2}$$

Note, the signal dimension is independent of the center frequency of telecommunication channel, it is determined by the product of channel bandwidth and bit duration.

C. Characterization of basis functions

A weighted sum of a few basis functions are used in digital communications to generate each element of signal set [2]. The basis functions are assigned by the modulation scheme, consequently they are *a priori* known.

According to the Fourier analyzer concept, the received signal space is constructed from the observation time period T and it is spanned by the the harmonically related

$$\cos(k\frac{2\pi}{T}t) \quad \text{and} \quad \sin(k\frac{2\pi}{T}t) \tag{3}$$

functions, where $K_1 \le k \le K_2 = K_1 + S_D/2 - 1$. Constants K_1 and K_2 are determined by the lower and upper, respectively, cut-off frequencies of bandpass channel filter.

Let the nth basis function $g_n^q(t)$ be projected to the received signal space. Then its image, i.e., its Fourier coefficients are

$$\begin{aligned} \alpha_{nk}^q &= \frac{2}{T}\int_0^T g_{T,n}^q(t)\cos(k\frac{2\pi}{T}t)dt, \\ \beta_{nk}^q &= \frac{2}{T}\int_0^T g_{T,n}^q(t)\sin(k\frac{2\pi}{T}t)dt. \end{aligned} \tag{4}$$

By means of the Fourier coefficients, the nth basis function is obtained in the received signal space as

$$g_{T,n}^q(t) = \sum_{k=K_1}^{K_2}\left[\alpha_{nk}^q\cos(k\frac{2\pi}{T}t) + \beta_{nk}^q\sin(k\frac{2\pi}{T}t)\right]. \tag{5}$$

Like $\tilde{r}_{T,m}(t)$ in (1), the periodic function $g_{T,n}^q(t)$ is identical with the basis function $g_n^q(t)$ over the observation time period.

The upper index q in (5) reflects that the basis functions are continuously varying in chaos-based communications. In fixed waveform communication the basis functions are fixed, therefore, q is dropped.

D. Chaos-based communications: An inevitable loss in a priori information

A priori information is exploited by the detection algorithm to suppress the effect of channel noise and interference. The detection may be performed even if only a very limited amount of *a priori* information is available or exploited at the receiver, but the less the *a priori* information, the worse the BER.

The sources of *a priori* information are the basis functions. In the Fourier analyzer concept, the measure of available *a priori* information relates to how precisely the Fourier coefficients of basis functions are known at the receiver.

If a coherent receiver [2] is used in fixed waveform communications then the basis functions, i.e., its Fourier coefficients are exactly known at the receiver. Consequently, these systems offer the best BER over an additive white Gaussian noise (AWGN) channel [2].

In the case of chaos-based communications two inevitable sources of losing *a priori* information exist:

1) Because the behavior of chaotic signals can only be modeled by stochastic signal model, the chaotic basis functions have no Fourier transform, instead, they have only power spectral density. Consequently, the phase information is lost and only the magnitudes of Fourier coefficients defined by (4) are available.
2) The upper index q in (4) indicates that the Fourier coefficients are random variables. During the development of detection algorithm, i.e., the receiver design, we can use only the mean value of Fourier coefficients to distinguish the desired signal from noise and interferences.

Chaos-based communication systems suffer from an inevitable loss in *a priori* information. Consequently, their BER always lags behind that of the fixed waveform communication systems. If a potential application is searched for the chaos-based systems then such applications should be found where the theoretical loss in *a priori* information is less important.

III. POSSIBLE APPLICATIONS OF CHAOS-BASED COMMUNICATIONS COMMUNICATION

The main conclusion of previous section is that chaos-based communications cannot be used if (i) very low BER and (ii) high data rate are must.

However, there are many other applications such as wireless networking devices of embedded systems or sensor networks [3], [4] where the average data rate is very low, the QoS is assured by an acknowledgment protocol and the power consumption is one of the main challenges of implementation. These systems are referred to as Low Rate-Wireless Personal and Low Rate-Wireless Local Area Networks (LR-WPAN and LR-WLAN, respectively) in the literature. WPAN and WLAN systems differ in the coverage range, the former is intended to cover an area in which a human being operates (typical range goes from 15 m to 30 m, this range is referred to as picocell), while the latter one covers a microcell where the typical range of coverage is about 100 m.

The most important application-specific requirements of LR-WPAN/LR-WLAN applications are as follows:

- These mobile communication systems are used in indoor, where the time-variant channel suffers from multipath propagation [5].
- There are no dedicated frequency bands for the users, communications has to be established in the ISM frequency bands or the already occupied frequency bands have to be re-used.
- The required average data rate is very low and some latency time (about 10 ms) can be tolerated.
- According to the Standards IEEE 802, these systems operate with with variable-size packets.
- The raw BER is not a big issue because the QoS is assured by an acknowledgment protocol.
- The power consumption is essential, a radio node must operate at least for two years using an AAA-type battery.
- The price must be below USD10.00, consequently, CMOS technology has to be used for implementation. The application of RF analog filters should be avoided. Due to the ultra-low power consumption, low price and CMOS technology, only very simple system architecture can be used. The application of complex modulation schemes and the usage of complex quality improvement techniques (see rake receiver as an example) are not allowed.
- The overall network has to work without an infrastructure and it must have a self-organizing and self-healing capability in order to establish and maintain ad-hoc networks without any human interaction.

IV. ULTRA-WIDEBAND RADIO

By now, telecommunication engineers have run out of the empty radio frequency bands where cheap CMOS radio transceivers may be implemented. The only way that makes the accommodation of new radio communication systems possible is the frequency re-use, where a new radio system operates over a frequency band that is already occupied by conventional, mostly narrowband, telecommunication systems. To avoid the interference caused in the already existing conventional systems the spectrum of the new radio system must be spread over an *ultra-wide frequency band*.

As shown in Fig. 2, the Power Spectral Density (psd) of Equivalent Isotropically Radiated Power (EIRP), measured with a resolution of 1 MHz, must be less than -41.3 dBm [6]. To calculate the maximum allowable radiated EIRP we have to consider that the bandwidths of narrowband and wideband UWB systems are 500 MHz and 2 GHz, respectively. The EIRP of UWB systems is extremely low, for the narrowband and wideband systems its values are 37 μW and 148 μW, respectively.

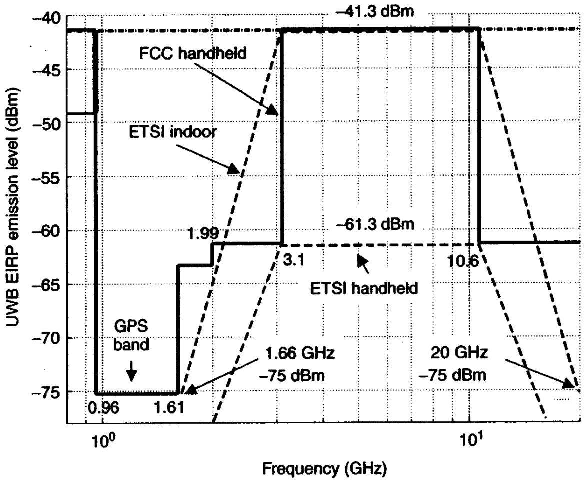

Fig. 2. Emission limits for handheld and indoor UWB systems allowed by the European Technical Standards Institute (ESTI), dashed curve, and the Federal Communications Commission (FCC, USA), solid curve [6].

The frequency band allocated to the UWB devices goes from 3.1 GHz to 10.6 GHz. By definition, the UWB transmitter is an intentional radiator that, at any time instant, has a fractional bandwidth greater than 20% or an UWB bandwidth greater than 500 MHz. On the other hand, UWB regulations specify only the maximum emission limit and minimum bandwidth and say nothing about the type of carrier and the technique used to generate the modulated UWB waveform.

V. COMPARISON OF CHAOS-BASED AND IMPULSE RADIOS

Since the UWB regulations give only the rule under which the assigned frequency band may be accessed, the UWB carrier may be either (i) an impulse or (ii) chaotic waveform.

A. UWB impulse radio

In a strict sense the spectrum of an UWB pulse covers the entire frequency band. Definition of UWB bandwidth and constraints on radiated UWB signal are shown in Fig. 3.

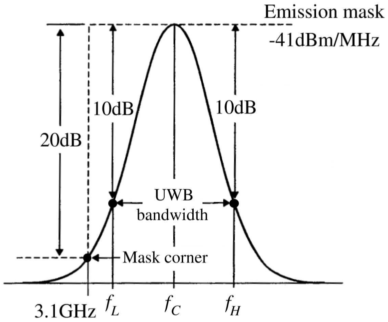

Fig. 3. Definition of UWB bandwidth and constraints on radiated UWB signal in the frequency domain. f_L and f_H denote the lower and upper, respectively, cut-off frequencies.

One of the main challenges in UWB impulse radio is the generation of an UWB pulse that satisfies the emission mask plotted in Fig. 3. Because of their excellent spectral properties the following UWB pulse shapes are considered during the theoretical investigation: (i) Gaussian pulse [7], (ii) frequency-shifted bell-shaped Gaussian pulse [6], (iii) monocycle [7], and (iv) doublet pulse [7].

After having generated a modulated UWB pulse satisfying the emission mask, an optimum UWB receiver has to be developed. Since the UWB pulses belong to the class of fixed waveform communications, the optimum receiver over an AWGN channel is the coherent correlation receiver that requires the recovery of unmodulated UWB pulses with perfect timing at the receiver.

The duration of UWB pulses is less than 3 ns and 1 ns in the narrowband and wideband, respectively, systems. The exact timing required by coherent detection cannot be assured with the CMOS technology for these ultra short pulse durations. Therefore, only noncoherent receivers may be built [8].

The following noncoherent receiver configurations can be found in the literature: (i) On-Off Keying (OOK) with energy detection [8], (ii) Pulse Polarity Modulation (PPoM) with template detection [6], and (iii) TR-based autocorrelation receiver [8] where TR stands for Transmitted Reference systems.

B. Chaos-based UWB radio

COOK with energy detection and FM-DCSK with TR-based autocorrelation receiver were proposed for the implementation of, and were used to build chaos-based data communication systems a long time ago. For a survey of chaos-based communication systems refer to [9].

In chaos-based systems the communications is performed with continuously varying waveforms. Therefore, only the energy detection approach and the autocorrelation receiver, together with its variants, can be used to recover the digital message signal.

C. Performance comparison

If OOK with energy detection or TR-based autocorrelation receivers are used then the same amount of *a priori* information is exploited in both the chaos-based system and UWB impulse radio. Consequently, the noise performances of the two solutions are identical.

UWB impulse radio may use another noncoherent modulation scheme, the PPoM with template detection. The noise performance of PPoM with template detection was evaluated in [10] and was found that its performance is very close to or slightly worse than that of the TR-based autocorrelation receiver.

VI. CONCLUSION

Only noncoherent receivers can be used for demodulation in both UWB impulse radio and chaos-based communication systems. Therefore, the system performances of the two solutions are almost identical.

The generation of an RF UWB pulse with CMOS circuitry is a very hard problem. If simple RF chaotic signal generators will be developed then chaos-based systems will offer a better solution to the implementation of UWB communication systems.

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