Novel wireless modulation technique based on noise

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***Abstract*— In this paper, a new RF modulation technique is presented. Instead of using sinusoidal carriers as information bearer, pure noise is applied. This allows very simple radio architectures to be used. Spread-spectrum based technology is applied to modulate the noise bearer. Since the transmission bandwidth of the noise bearer can be made very wide, up to ultra-wideband regions, extremely large processing gains can be obtained. This will provide robustness in interference-prone environments. To avoid the local regeneration of the noise reference at the receiver, the Transmit-Reference (TR) concept is applied. In this concept, both the reference noise signal and the modulated noise signal are transmitted, together forming the bearer. The reference and modulated signals are separated by applying a time offset. By applying different delay times for different channels (users) a new multiple access scheme results based on delay: Delay Division Multiple Access (DDMA). A theoretical analysis is given for the link performance of a single-user and a multi-user system. A testbed has been built to demonstrate the concept. The demonstrator operates in a 50 MHz bandwidth centered at 2.4 GHz. Processing gains ranging from 10–30 dB have been tested. The testbed confirms the basic behavior as predicted by the theory.**

I. INTRODUCTION

The release, by the United States Federal Communication Commission (FCC), of new rules for the application of Ultra-Wideband (UWB) systems [1], has proven to be a powerful stimulus to the study of UWB modulation. Ultra-Wideband signals are defined as signals with either a fractional bandwidth of at least 20%, or an absolute bandwidth of at least 500 MHz. UWB systems are immune to multipath effects in frequency-selective, fading environments. The very large UWB receiver bandwidth facilitates resolving separate multipath signals. Immunity to multipath,means that fading margins are not in fact required, so that UWB transmitter output power can be quite low.

UWB systems occupy broad spectral bandwidths, and will, therefore, most likely have to coexist with other (radio) systems utilizing the same RF spectrum. In order to minimize interference to other systems, the FCC requires that the UWB transmitted signal possess very low power density levels. In contrast, UWB systems must be able to deal with (strong) interference from these other (radio) systems since the overlap in frequency may be rather large. Interference can be coped with by avoidance or suppression. Since avoidance is hardly an option for wideband communications, the UWB receivers must be able to suppress the interference from narrowband jammers. Due to near-far proximity and the transmit power level of the jammers, the interfering signal can be as much as 30 or 40 dB greater than the level of the desired signal.

Suppression can be obtained by trading off data rate for robustness. Spread-spectrum techniques can be used to provide this robustness. The robustness of a spread-spectrum signal is embedded in the processing gain which is the ratio between the transmit bandwidth and the data rate. Since we are considering very large processing gains—in the order of 30 to 40 dB—this results in Ultra-Large-Processing-Gain (ULPG) systems. A challenge in spread-spectrum systems, with large processing gains, is signal acquisition at the receiver. Prior to synchronization, de-spreading can not be activated and the received signal has to be retrieved at very low SNR levels. In particular, when data traffic is bursty or packet-based, the acquisition time must be short.

It is anticipated that UWB systems due to their spectral bandwidth should prove amenable to very low-cost implementation. The is associated with selectivity and accuracy requirements for both the filter components and the frequency synthesis components which are quite relaxed. In addition, UWB allows completely new modulation schemes, based on changing the frequency and/or amplitude of a sinusoidal carrier used as information bearer.

II. BASIC PRINCIPLE

A. Bearer format

Classical radio transceivers make use of sinusoidal bearers. The information is embedded in the amplitude and/or phase of the frequency carrier. The UWB technique allows alternative bearer formats. The initial UWB techniques used very short pulses with a duration of less than a nanosecond [2]. The information is then embedded by applying Phase Shift Keying (PSK) or Pulse Position Modulation (PPM). Recently, more advanced systems have been introduced with longer pulses (several hundreds of microseconds) where the modulation is based on Orthogonal Frequency Division Multiplexing (OFDM) [3]. Pulsed systems do not produce a flat spectrum. Jitter reduction techniques are necessary to remove the spiky output. In addition, pulsed systems put extra requirements on peak power behavior.

More radical techniques for creating a bearer format result from chaotic systems [4]. Chaotic signals are non-periodic and ”noiselike”, but possess a deterministic structure so that they can be reproduced. In chaotic systems, a small perturbation causes a large change in the state of the system. Chaotic signals are good candidates for UWB bearers.

The lowest-cost bearer consists only of noise. Pure noise with a flat spectrum and an arbitrary amplitude distribution can quickly be generated at low cost. In addition, it will appear to be (thermal) noise to the other overlaying radio systems. Its bandwidth can be made very large and the peak-to-average ratio is reasonable. Pure noise is, therefore, a good candidate for UWB bearers as will be demonstrated in the remainder of this paper.

B. Transmit reference

As noted in the introduction, the biggest challenge for systems with Ultra-Large Processing Gain is the acquisition of the signal in the receiver. Conventional direct-sequence spread-spectrum systems store a replica of the spreading signature in the receiver that acts as a reference. Searching techniques are applied to synchronize the reference with the received signal in order to obtain full correlation. However, in the case of pulses with jitter and very low SNR values, the acquisition procedure in pulsed UWB will be a lengthy process. For the synchronization of chaotic signals, in principle, no stored reference is needed as was shown in [5]. However, fast acquisition under very low SNR conditions is not possible. If the bearer is a pure noise signal, as described in the current paper, it is not possible to generate a reference at all.

To obtain fast acquisition in the ULPG system, the reference is not generated in the receiver, but included in the transmitted signal. In the transmit-reference system, the modulated and unmodulated bearer are both transmitted by the transmitter. At the receive side, the reference signal and modulated signal are combined in order to despread the modulated signal. If the reference and modulated signals do not need to be extracted separately, the acquisition can take place under very low SNR conditions.

To distinguish between the reference and the modulated signals, the signals can be offset in time. An UWB system based on pulses and a delayed reference is presented in [6]. Also chaotic-based systems with a delayed reference have been described in [7] and [8]. The Differential Chaos Shift Keying (DCSK) technique presented in [7] is based on the well-known DPSK scheme with the difference that in DPSK, each symbol has the same format and can therefore be used as reference for the next symbol. In DCSK, each information symbol is paired with its own reference symbol. The disadvantage of this system is the rather large time delay, because the time delay is based on the data rate. For data rates in the order of a few hundred kb/s, microseconds of delay are required. Moreover, the need for a variable delay mechanism in order to use the delay as a multiple access technique, may well lead to implementation difficulties. In [8], Correlation Delay Shift Keying (CDSK) is described which uses chaotic signals in combination with a delayed reference.

In the system presented in this paper, the time delay is independent of the data rate. In contrast, the delay is related to the coherence time of our noise reference source. The coherence time is inversely proportional to the bandwidth of the noise reference. For UWB applications, this bandwidth is very large, in the order of a few Ghz. This results in manageable time delays in the order of nanoseconds.

C. Transceiver construction

The basic schemes for the transmitter and receiver are shown in Figure 1. The noise reference $c(t)$ can have any characteristic. For our analysis we have assumed a band-limited, spectrally flat signal with Gaussian amplitude distribution. The reference signal is divided over two branches. The upper branch carries the clean reference signal; the lower branch applies a time delay of τ_{Tx}. The modulation signal $m(t)$ can either be applied to the lower or the upper branch. The modulation applied is BPSK, that is, $m(t)$ is assumed to be a polar, NRZ signal.

The received signal is multiplied (correlated) with a delayed version of itself. It is clear that the de-spreading takes place in the RF domain. The de-spreaded signal $z(t)$ is subsequently filtered (or integrated-and-dumped) and symbol detection is used to retrieve the detected signal $m(t)$.

Figure 1 shows that very few components are required. De-spreading takes place in the RF domain, and after correlation, the information directly appears at baseband. For proper operation, the reference signal and modulated signal should be made mutually incoherent by choosing $\tau_{\mathrm{Tx}} \gg \tau_{\mathrm{c}}$, where τ_{c} is the coherence time of the noise source. For optimal de-spreading the delay values at transmitter and receiver should be identical: $\tau_{\mathrm{Rx}} = \tau_{\mathrm{Tx}}$. If they differ, no de-spreading results. By selecting different $\tau_{\mathrm{Tx},i}$ values for different users, a multiple access technique based on delay results: Delay Division Multiple Access (DDMA).

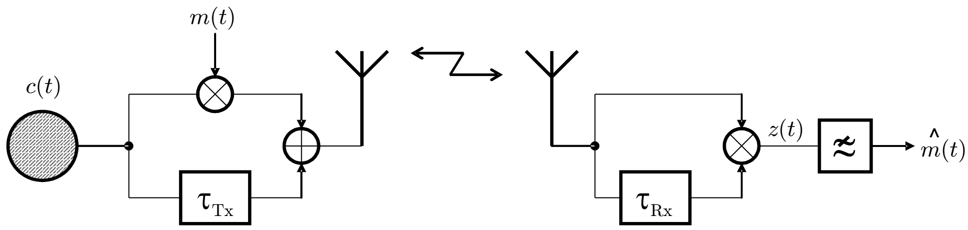

Fig. 1. Basic schemes for transmitter and receiver.

III. Link performance in AWGN

A. Noise performance

The system as described in Section II-C shows many similarities with a system applied in optical communications. The optical technique is called Coherence Multiplexing [9]. The performance of the Coherence Multiplexing (CM) system is limited by the self-interference—also called beat noise. This is caused by the interference between the reference and its time-shifted, modulated replica. Since self-interference is independent of signal power, it will result in an error floor in the BER analysis.

The analysis for the ULPG system described in this paper largely follows the analysis of the CM system [9]. In a radio environment, in addition to the self-interference, the thermal noise introduced at the receiver input (i.e. channel noise) plays a major role. Trade-offs can be made between thermal noise and self-interference.

For the noise analysis, the following assumptions are made. At the transmitter, the energy of the noise reference $c(t)$ is equally divided between the two branches. That this indeed leads to optimal performance can be shown by a straightforward analysis, but is skipped here. The noise reference has a Gaussian amplitude distribution with a mean of zero. The RF channel is assumed flat. The thermal noise $n(t)$ that is added at the receiver input is considered to be additive white Gaussian noise (AWGN). For a proper noise analysis, a bandpass filter with a transfer function $H(f)$ is assumed at the receiver input (as shown in Figure 1).

B. Single-user performance

In this section, the link performance under AWGN for a single user is given. Due to space constraints, only the major results of the system analysis are given here. The reader is referred to [10] for a complete analysis. Crucial for the link performance is the SNR of $z(t)$ directly after de-spreading. This SNR is given by (1).

In this equation, $S_{cc}(f)$ is the power spectral density of the noise reference at the input of the receiver, N_0 is the power spectral density of the channel noise, $H(f)$ the filter response at the input of the receiver, and T_b is the bit time. The received bit energy is given by

$$E_\mathrm{b} = 2T_\mathrm{b} \int_{-\infty}^{\infty} S_{cc}(f)\,\mathrm{d}f\,. \tag{2}$$

The factor 2 results from the fact that both the energy in the clean reference and the time-shifted, modulated reference must be taken into account. If we assume the power density spectrum $S_{cc}(f)$ is flat over a bandwidth W, and also a flat filter response $H(f) = 1$ over a bandwidth W, the SNR as a function of E_b/N_0 is given by

$$SNR = \frac{2\left(\frac{E_\mathrm{b}}{N_0}\right)^2}{7\left(\frac{E_\mathrm{b}}{N_0}\right)^2 \dfrac{1}{G} + 8\frac{E_\mathrm{b}}{N_0} + 4G}\,, \tag{3}$$

where the processing gain G is equal to the time-bandwidth product

$$G \triangleq T_\mathrm{b} W\,. \tag{4}$$

It can be proven that—for large values of the SNR—the bandwidth of the noise at the input of the detection filter is much larger than the bandwidth of this filter. Hence, the noise can be considered Gaussian distributed. Since BPSK is applied, the BER performance can be simply derived from the SNR as

$$P_\mathrm{b} = \mathrm{Q}\left(\sqrt{SNR}\right)\,, \tag{5}$$

where $\mathrm{Q}(.)$ is the Gaussian tail probability

$$\mathrm{Q}(x) \triangleq \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} \exp\left(-\frac{z^2}{2}\right)\,\mathrm{d}z\,. \tag{6}$$

The denominator in (3) consists of three terms. The first term represents the self-interference, that is the mixing between the reference and its time-shifted replica. The second term results from the mixing between the channel noise and the signal. Finally, the third term results from the channel noise only. When the signal energy is large, the channel noise can be ignored, and the SNR reduces to $SNR_\mathrm{floor} = 2G/7$. Clearly, this results in the error floor mentioned before. Since the error floor will be inversely proporional to SNR_floor, a high processing gain will result in a lower error floor. The BER as a function of E_b/N_0 is shown in Figure 2. In this figure, the performance is also shown when the optimal processing gain G is selected for each E_b/N_0 value.

The SNR varies with the processing gain G. Increasing G will suppress the self-interference, but will increase the effect of the channel noise. For a constant transmit power and constant data rate, an increase in G results from an increase of W; this will increase the contribution of the channel noise N_0. Clearly, for a specific E_b/N_0, an optimal G can be found which is given by

$$G_\mathrm{opt} = \tfrac{1}{2}\sqrt{7}\frac{E_\mathrm{b}}{N_0}\,. \tag{7}$$

Figure 3 shows the BER as a function of G for several values of E_b/N_0. For increasing G, the BER slowly rises.

$$SNR = \frac{\left[\int_{-\infty}^{\infty} |H(f)|^2\, S_{cc}(f)\,\mathrm{d}f\right]^2 T_\mathrm{b}}{7\int_{-\infty}^{\infty} |H(f)|^4\, S_{cc}^2(f)\,\mathrm{d}f + 2N_0 \int_{-\infty}^{\infty} |H(f)|^4\, S_{cc}(f)\,\mathrm{d}f + \frac{1}{4}N_0^2 \int_{-\infty}^{\infty} |H(f)|^4\,\mathrm{d}f} \tag{1}$$

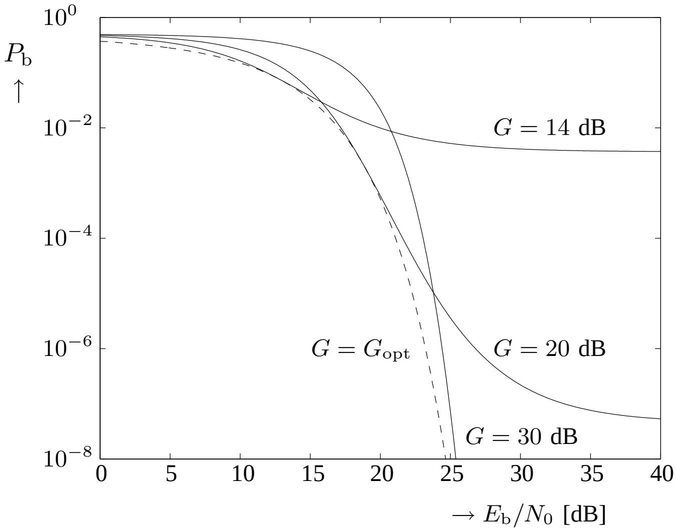

Fig. 2. Bit error rate as a function of E_b/N_0 for different values of the processing gain G. In the dashed curve, the processing gain is optimized for each value of E_b/N_0.

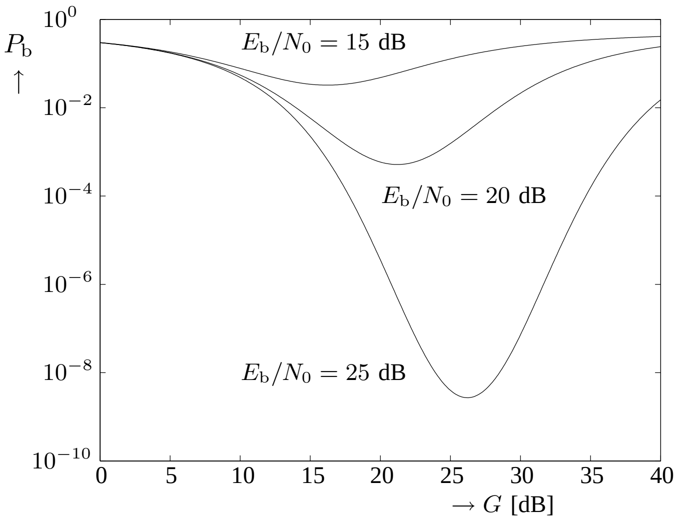

Fig. 3. BER as a function of the processing gain G for several values of E_b/N_0.

C. Multi-user performance

The equations presented in the previous section can be extended to multiple users. We assume the noise references to be uncorrelated (which is highly likely as they are generated in different transmitters) but with an equal bandwidth. To avoid any crosstalk during the de-spreading operation, the difference between the time offset $\tau_{\mathrm{Tx},i}$ of user i and the time offset $\tau_{\mathrm{Tx},j}$ of user j should be larger than the coherence time of the noise references:

$$|\tau_{\mathrm{Tx},i} - \tau_{\mathrm{Tx},j}| \gg \tau_\mathrm{c} \, , \, i \neq j \, . \tag{8}$$

Assuming a flat and bandlimited reference spectrum $S_{c_i c_i}$, and a corresponding flat and bandpass filter response $H_i(f)$, the SNR for a multi-user case becomes:

$$SNR = \frac{2\left(\frac{E_\mathrm{b}}{N_0}\right)^2}{(4M^2+2M+1)\left(\frac{E_\mathrm{b}}{N_0}\right)^2 \frac{1}{G} + 8M\frac{E_\mathrm{b}}{N_0} + 4G} \, . \tag{9}$$

where M is the number of users. In this case, all M signals are received at the same power level. The BER as a function of E_b/N_0 with the number of users M as a parameter, is shown in Figure 4. A processing gain of 30 dB was assumed.

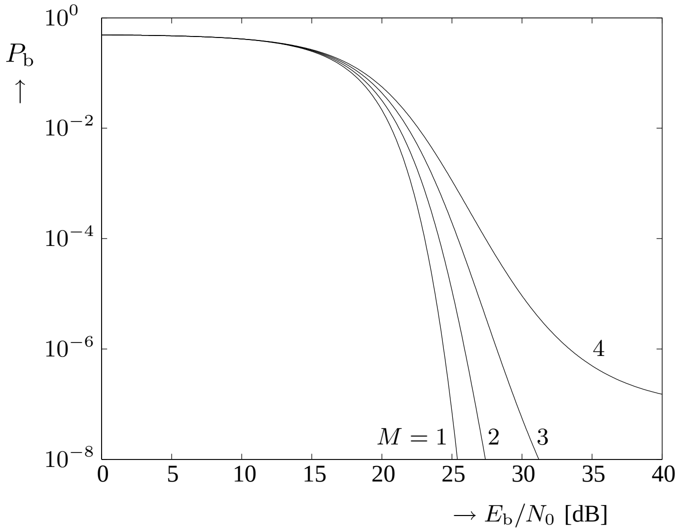

Fig. 4. Bit error rate as a function of E_b/N_0 for 1, 2, 3 or 4 users, for a processing gain $G = 30$ dB.

In an interference-limited environment, the channel noise is of minor importance. In that case, only the self-interference (and cross-interference) of the users is important. The error floor is given by

$$P_{\mathrm{b,floor}} = \mathrm{Q}\left(\sqrt{\frac{2G}{4M^2+2M+1}}\right) \tag{10}$$

The error floor as a function of the number of users with G as a parameter is shown in Figure 5.

We can derive from (10) that for a given BER performance, the number of users that can be accommodated is proportional to the square root of the processing gain.

IV. Testbed

A demonstrator has been built with discrete components in order to tryout the concept. Only off-the-shelf components have been used. An extensive description of the testbed can be found in [11].

A. Measurement setup

The complete testbed is shown in Figure 6. The setup consists of three parts: a transmitter (Tx), a receiver (Rx), and the measurement and data generation equipment. The transmitter is shown in Figure 7. The noise reference was emulated by a pseudorandom chip sequence with a rate of

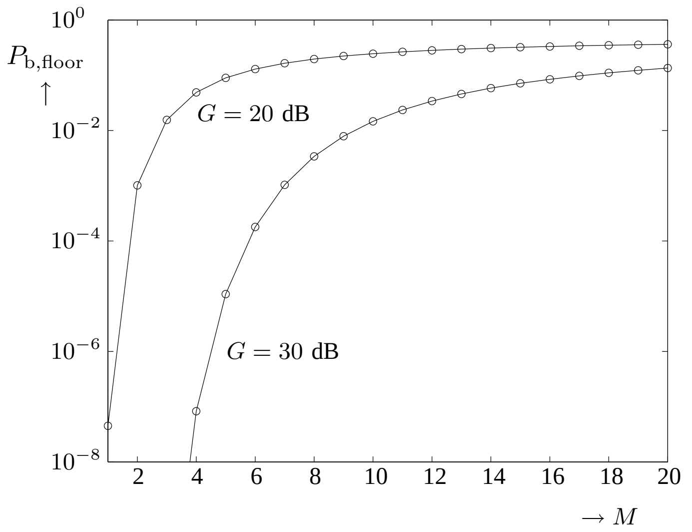

Fig. 5. BER floor as a function of the numbers of users M for different values of the processing gain G.

50 Mchips/s centered at a carrier frequency of 2.44 GHz. This sequence was generated by an Agilent E4438C Vector Signal Generator. Pulse shaping was applied, so that the frequency spectrum was flat over the bandwidth W. For the testbed, the bandwidth W was limited to 50 MHz. The noise reference was divided over the two branches using a (passive) power splitter. One branch was subsequently delayed using a coax cable of a few meters. Since the coherence time of the noise reference is about 20 ns, a cable of 5 m length is already sufficient to obtain $\tau_{\mathrm{Tx}} > \tau_{\mathrm{c}}$. In the other branch, a mixer is placed to multiply the data signal with the noise reference. For the data signal, a HP 3762A data generator has been used. To study different processing gain values, the reference bandwidth W was kept constant, where as the data rate of the modulating signal was varied between 50 kb/s and 2 Mb/s. Finally, the two branches were combined in a passive combiner. The receiver is shown in Figure 8. A SAW bandpass filter centered at 2.441 GHz selects the ISM band. The received signal is then amplified and distributed over two branches. The upper branch includes a coax cable for providing the delay, and a phase shifter for the fine tuning of the delay. The two RF signals are then mixed resulting in a baseband signal. The baseband signal is filtered and amplified again. Amplifiers (LNA: low-noise amplifier) at different places were required to obtain the proper power levels for the discrete components. In order to do BER measurements, an HP 3763 Error Detector was used. A common clock generator HP 33120A was used to time-synchronize the data generator and error detector. The channel noise was emulated by the same signal providing the noise reference. A sufficiently large delay was applied to provide a noise signal uncorrelated with the reference signal. The power level of the channel noise could be varied to obtained the BER values as a function of E_{b}/N_0.

B. Results

The measured results are summarized in Figure 9. The behavior predicted by theory can clearly be observed. Lower values of processing gain result in higher error floor values. Larger processing gain values show a steeper fall off, but also at higher E_{b}/N_0 values. The measurement results for $G = 20$ dB and 30 dB are shifted to the right with about 2–3 dB which can be attributed to extra noise sources in the testbed which have not been taken into account in the theoretical analysis. However, the noise floor for $G = 14$ dB

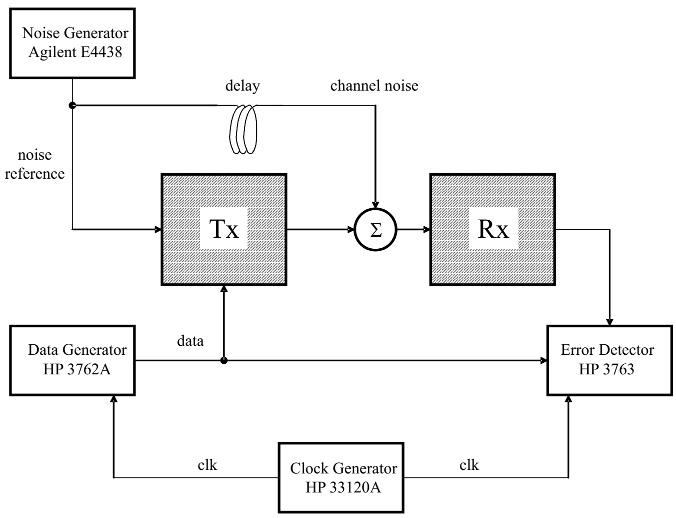

Fig. 6. Overview of the complete testbed.

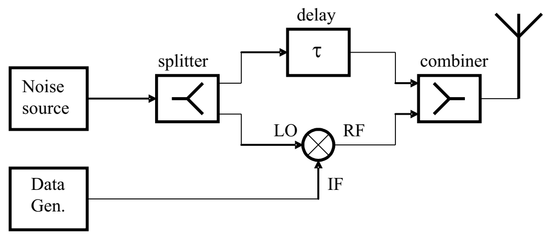

Fig. 7. Block diagram of transmitter section.

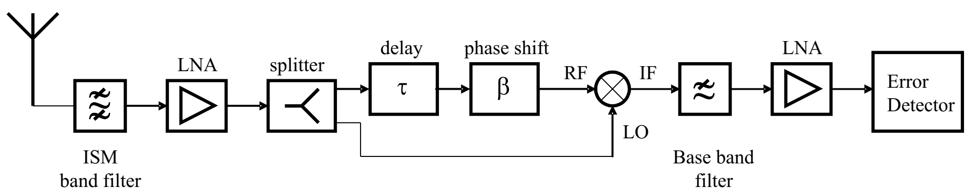

Fig. 8. Block diagram of receiver section.

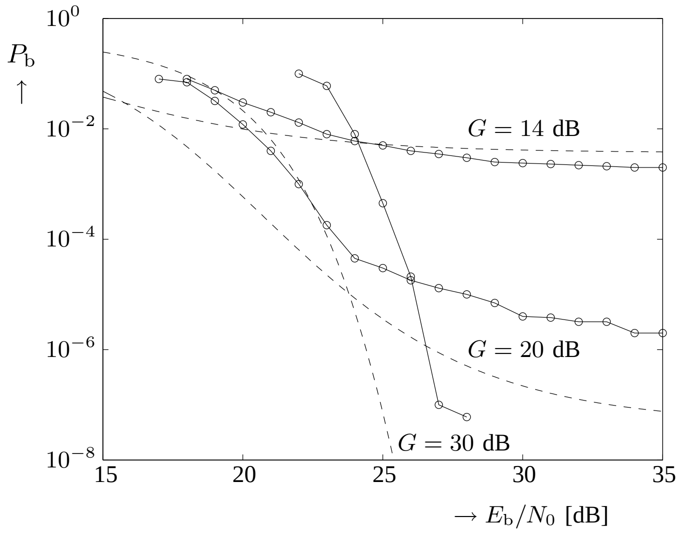

Fig. 9. Measured bit error rates as a function of E_b/N_0 for different values of the processing gain G. The dashed curves correspond to the theoretical values.

is better (lower) than predicted by theory. In addition to the extra noise sources, there is another important difference with the theoretical analysis. The theory assumed a noise reference with a Gaussian amplitude distribution. The demonstrator used a pulse-shaped NRZ chip sequence which has a discrete amplitude distribution. The amplitude distribution has an impact on the error floor. For example, in [8] a chaotic reference with a uniform amplitude distribution is used, yielding lower error floors. The problem with references having a uniform or Gaussian amplitude distribution is the variation in the bit energy E_b: due to the random behavior, the bit energy may differ from symbol to symbol. The variation in bit energy may be removed by hard-limiting the reference signal $c(t)$ before feeding it into the transmit section. An additional contributor to the discrepancy between theory and practice is the difference in channel noise. In the theoretical analysis, the channel noise was assumed to be AWGN, however, in our tests it was the delayed chip sequence in the demonstrator.

V. Discussion

The modulation scheme based on a time-offset reference combines ultra-large processing gain with fast acquisition time and very low implementation cost. Since no high-Q filters are required, nor accurate VCOs, power consumption and cost, even at these large bandwidths can be kept rather low. Compared to conventional modulation schemes like FM or PSK, the E_b/N_0 performance is somewhat inefficient since half of the transmitted power is required for the reference signal. Fortunately, for short-range communications, transmit power is not a limiting factor. In fact, for short-range UWB communications, it is the processing power rather than the transmit power which determines the overall power consumption. Moreover, since an UWB can be used, no fading margin needs to be included in the link budget. This provides a 10–20 dB improvement compared to narrowband systems.

Increasing the processing gain reduces the error floor caused by the self-interference. The processing gain also provides the robustness for narrowband interference. Although not described in this paper, narrowband interference can effectively be suppressed by the ULPG system. When the coherence time of the narrowband interference is much larger than the delay τ_Rx in the receiver, the jammer is basically squared. It will therefore turn up as a spike at DC. When the modulating signal $m(t)$ can be moved away from DC, the DC jammer can be filtered out by the baseband filter. This can be accomplished by using Manchester line coding for $m(t)$, since this line coding does not have a DC component.

It has also been shown that time-offset modulation can be used in a multi-user environment. Compared with conventional direct-sequence spread-spectrum systems, time-offset modulation cannot accommodate a large number of users. However, it is more appropriate to compare the time-offset system with a DSSS system lacking code synchronization. Cross-mixing will result in degraded performance, which is also the case for the time-offset system.

The testbed implementation used a modest bandwidth of 50 MHz because of limitations in instrumentation. The concept can, however, easily be extended to larger transmission bandwidths with UWB characteristics. This will not have a major effect on the results as long as flat channels are considered. The performance of the system when subjected to frequency-selective fading is yet to be studied.

VI. Conclusions

In this paper we presented a new modulation scheme in which noise is used as an information bearer. A transmit-reference technique is used to allow the receiver to synchronize to the bearer. Analytical expressions have been given for the link performance of a single-user and a multi-user environment. A testbed has been built to demonstrate the feasibility of the concept. Measurements confirmed the behavior of the system.

Using the proposed concept, ultra-large processing gain systems can be built which effectively suppress narrowband interference and, thereby, support overlaying with existing systems. The method provides transparency, which means that the concept dictates neither the modulation scheme nor the multiple access scheme. A range of different modulation schemes can, therefore, be used, both analog and digital. In addition, it can be applied in FDMA, TDMA, and CDMA systems. In particular, the delay itself can act as a user identifier supporting a new multiple access scheme based on Delay Division Multiple Access (DDMA). Since signal acquisition is nearly instantaneous (without the need for excessive power) it can readily be used for packet-based communication systems.

References

[1] Federal Communications Commission, Part 15 – Radio Frequency Devices, December, 2003.

[2] M. Z. Win, R. A. Scholtz, "UWB time-hopping spread-spectrum impulse radio for wireless multiple-access communications," *IEEE Transactions on communications*, vol. 48, no. 4, pp. 679–691, April, 2000.

[3] A. Batra, ”Design of a multiband OFDM system for realistic UWB channel environments”, *IEEE Transactions on Microwave Theory and Techniques*, vol. 52, no. 9, pp. 2123–2138, Sept., 2004.
[4] C. Williams, ”Chaotic communications over radio channels,” *IEEE Transactions on circuits and systems – I: fundamental theory and applications*, vol. 48, no. 12, , pp. 1394–1404, Dec., 2001.
[5] L. M. Pecora, T. L. Caroll, ”Synchronization in chaotic systems,” *Physical review letters*, vol. 64, no. 8, pp. 821–824, Feb., 1990.
[6] N. van Stralen, A. Dentinger, K. Welles II, R. Gaus Jr., R. Hoctor, H. Tomlinson, ”Delay hopped transmitted reference experimental results,” *Proc. IEEE Conf. on Ultra Wideband Systems and Technologies*, 2002, pp. 93–98.
[7] G. Kolumbán, M. P. Kennedy, Z. Jácó, G. Kis, ”Chaotic communications with correlator receivers: theory and performance limits,” *Proceedings of the IEEE*, vol. 90, no. 5, pp. 711–732, May, 2002.
[8] M. Sushchik, L. S. Tsimring, A. R. Volkovskii, ”‘Performance analysis of correlation-based communication schemes utilizing chaos,” *IEEE Transactions on circuits and systems – I: fundamental theory and applications*, vol. 47, no. 12, pp. 1684–1690, Dec., 2000.
[9] A. Meijerink, G. H. L. M. Heideman, W. van Etten, ”Balanced optical phase diversity receivers for coherence multiplexing,” accepted for publication in *IEEE/OSA Journal of Lightwave Technology*, vol. 22, no. 11, Nov., 2004.
[10] A. Bekkaoui, *Link performance of the time offset transmitted reference system*, Master’s Thesis, University of Twente, Enschede, The Netherlands, June, 2004.
[11] A. Taban, *Microwave radio testbed for a new modulation scheme based on time offset*, Master’s Thesis, University of Twente, Enschede, The Netherlands, June, 2004.