A new wireless modulation scheme based on frequency-offset

J.C. Haartsen, X. Shang, J.W. Balkema, A. Meijerink, J.L. Tauritz
Telecommunication Engineering
Faculty of Electrical Engineering, Mathematics, and Computer Science
University of Twente
j.c.haartsen@utwente.nl

***Abstract**: A new RF modulation scheme based on a frequency-offset technique is presented. Instead of using sinusoidal carriers, pure noise is applied as information bearer. The transmitted signal is a combination of modulated noise and unmodulated noise acting as a reference. The reference and modulated signals are separated by a frequency offset Δf which is much smaller than the transmission bandwidth. When using the technique, very large processing gains can be obtained which provides robustness in interference-prone environments. In addition, very simple transceiver implementations result. The paper shows both analytical and experimental results.*

1. Introduction

In the past decade, radio transmission based on Ultra-Wideband (UWB) technology has received a great deal of attention. 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. In the US, UWB systems may be operated from 3.1 to 10.6 GHz at rather low power spectral density (PSD) levels [1]. In Europe and the rest of the world, the regulatory rules have not as yet been finalized.

UWB systems are intended to overlay with other existing radio systems. This may result in mutual interference. The low PSD levels of the UWB transmitter should protect other, non-UWB receivers from interference. In contrast, UWB receivers will have to cope with (narrowband) interference from other, non-UWB transmitters. In order to deal with strong interference, the UWB system either has to avoid occupied spectrum or must suppress the interference. Suppression can be a challenge as the interference may be 30 to 40 dB higher in power (near-far effect and strong transmit power of non-UWB systems).

Suppression can be obtained by trading off data rate for robustness. This is applied in spread-spectrum techniques where the transmission bandwidth is much larger than the information bandwidth. The ratio between these bandwidths represents the processing gain and is a measure of robustness. Ultra-Large Processing Gain (ULPG) systems are useful in realizing suppression on the order of 30 to 40 dB. Receiver signal acquisition is a challenge in spread-spectrum systems with large processing gains. Prior to synchronization, de-spreading is not activated and the received signal has to be retrieved at very low SNR levels. This can be a problem in packet-oriented systems where traffic is burst like and acquisition times are very short.

In this paper, a new modulation technique is described which combines ultra-large processing gains with very short acquisition times. In addition, it is amenable to low-cost transceiver implementations. Higher order filters and complex synthesizers are avoided by making use of a very wideband noise signal.

2. Frequency-Offset Noise Modulation

Classical radio transceivers make use of sinusoidal bearers. The information is embedded in the amplitude and/or phase of the frequency carrier. As a result, tuned transceivers are required with tightly specified filters and stable oscillators. Simpler transceivers result when the information bearer is based on pure (wideband) noise. Pure noise with a flat spectrum and an arbitrary amplitude distribution can easily be generated at low cost. In addition, it will be experienced as (thermal) noise by other overlayed radio systems. Its bandwidth can be made very large and the peak-to-average ratio is reasonable. Noise as information bearer has been applied in optical communications, where it is known as Coherence Multiplexing [2]. Recently, it has been proposed for use in radio communications [3].

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. However, that is not possible when using a pure noise signature as proposed in this paper. In our case, the reference is neither stored nor regenerated in the receiver but included in the transmitted signal.

In the transmit-reference system, the modulated and reference signals are both transmitted by the transmitter. The additional reference signal results in a 3 dB hit to the link budget. Indeed in short-range applications, power consumption is mainly attributed to the RX/TX signal processing components rather than to the actual radio transmission.,The power associated with the reference forms no additional burden at the system level. To distinguish between the reference and the modulated signals, the signals must be separated. This can be accomplished using time offset as presented in [3], or by introducing frequency offset as presented in this paper. The frequency offset is obtained by mixing one of the signals with a low-frequency local oscillator (LO). Compared with the time-offset method, the frequency-offset method is more attractive as the offset frequency Δf can be easily varied by tuning the LO, and an LO/mixer combination can be more readily integrated on a chip than a delay element providing several microseconds of delay. In the receiver chain, the reference signal and modulated signal are combined in the RF domain and directly de-spread to the baseband domain.

The basic transmitter and receiver schemes of the frequency-offset system are shown in Figure 1. The noise signal $c(t)$ can have any characteristic. For our analysis we have assumed a band-limited, spectrally flat signal with Gaussian amplitude distribution. The noise signal is divided over two branches. The upper branch carries the clean reference signal; the lower branch applies a frequency offset of Δf. The modulation signal $m(t)$ can either be applied to the lower or 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 replica of itself which is frequency shifted by Δf. It is clear that the de-spreading takes place in the RF domain. The de-spread signal $z(t)$ is subsequently filtered (or integrated-and-dumped) and symbol detection is applied 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 following correlation, the information directly appears at baseband. For proper de-spreading the frequency offset at transmitter and receiver should be identical, $\Delta f_1 = \Delta f_2$. If they differ, no de-spreading to baseband results and the remaining signals are suppressed by the low-pass filter. By selecting a different Δf_i for different users, a multiple access technique based on frequency offset results: Frequency-offset Division Multiple Access (FODMA).

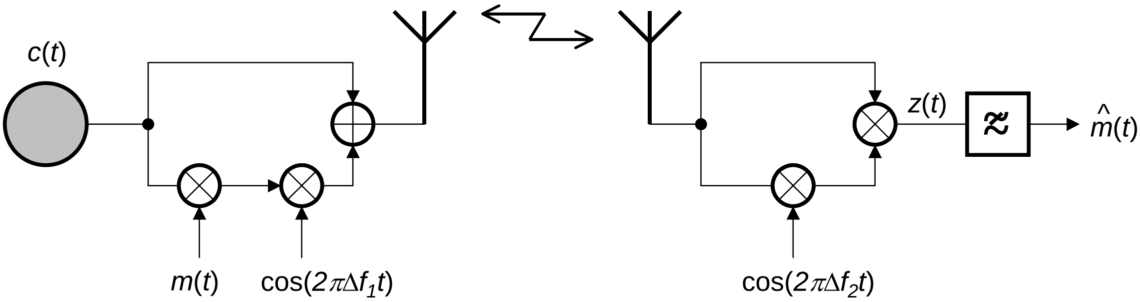

Figure 1: Basic transmitter and receiver schemes for the frequency-offset method

3. Link Performance in AWGN

In this section, we investigate the link performance of the FODMA system in additive white Gaussian noise (AWGN), in terms of the average error probability. We apply a specific value of the frequency offset to each transmitter. To avoid interference from different transmitters, the frequency offsets of every two transmitters should satisfy $|\Delta f_i - \Delta f_j| >> 1/T$, where T is the period of one bit [4].

Within one bit time T, the modulation signal of transmitter r, $m_r(t)$, is a constant m_r, being either +1 or -1. We assume that the noise signal $c(t)$ is Gaussian distributed, with mean value of zero. Both the PSD function of $c(t)$ and the transfer function of the channel filter $H(f)$ are band-limited flat, with bandwidth B_x. One can find that for the receiver with the same frequency offset as transmitter r, the expected value of $z(t)$ is proportional to $m_r(t)$ [4]. This ensures that for each transmitter, the transmitted data can be retrieved at the corresponding receiver. Thus, multiple access is realized in the FODMA system.

To evaluate the quality of the retrieved data, we investigate the signal-to-noise ratio (SNR) after integrate-and-dump filtering at the receiver that has the same frequency offset as transmitter r. For large values of the processing gain $G \hat{=} B_x T$, it can be proven that the noise part of $z(t)$, which can be calculated as $n(t) \hat{=} z(t) - \mathrm{E}[z(t)]$, has a bandwidth that is much larger than the data rate, so that $n(t)$ can be considered as additive white noise [4]. Hence the SNR after integrate-and-dump filtering becomes

$$SNR \approx \mathrm{E}^2[z(t)] \cdot T / S_n(0) , \qquad (1)$$

where $S_n(f)$ is the PSD function of $n(t)$, which can be found by calculating the autocorrelation function of $n(t)$ and then performing Fourier transformation. When equal power is received from each transmitter, and channel noise is AWGN with PSD $N_0/2$, then one can show:

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

where M is the total number of users and E_b is the received bit energy [4].

We assume that the modulation signal $m_r(t)$ takes the values of +1 and -1 with equal probabilities. Since the filter bandwidth is much smaller than the bandwidth of its input signal, the decision samples can be assumed to be Gaussian distributed. Hence one can find that the average error probability can be approximated as

$$P_\mathrm{e} \approx \mathrm{Q}\left(\sqrt{SNR}\right), \tag{3}$$

where Q(x) is the Gaussian tail probability

$$\mathrm{Q}(x) \mathrel{\hat{=}} \frac{1}{\sqrt{2\pi}} \int_x^\infty \exp\left(-\tfrac{1}{2} y^2\right) \mathrm{d}y\,. \tag{4}$$

The SNR can be maximized by choosing the processing gain G as $G = G_\mathrm{opt}$, where

$$G_\mathrm{opt} = \tfrac{1}{2}\sqrt{2M^2 + 4M + 1} \cdot \frac{E_\mathrm{b}}{N_0}, \tag{5}$$

resulting in

$$SNR_\mathrm{max} = \frac{1}{2\sqrt{2M^2 + 4M + 1} + 4M} \cdot \frac{E_\mathrm{b}}{N_0}, \tag{6}$$

where E_b/N_0 is the received SNR per bit. This results in a minimal value for P_e.

As a special case, when $M = 1$, the single-user performance of the system can be evaluated. Figure 2 plots P_e, under the condition that $M = 1$, as a function of E_b / N_0, based on different processing gains. It also shows the linear relationship between G_opt and E_b/N_0. As expected, the average error probability decreases, as E_b/N_0 increases. Furthermore, the curve of P_e in the optimal case, with $G = G_\mathrm{opt}$, never goes higher than those in the other cases, where the processing gains are constant. Thus, for a given E_b/N_0, the value of the processing gain should be taken as close to G_opt as possible, to achieve low average error probability. It may, however, not be practical to adjust the processing gain of the system from time to time. It would, therefore, be better to select a particular value for the processing gain, so that the system will perform with a close-to-minimal average error probability. For example, when it is known that the value of E_b/N_0 varies between 10 dB and 15 dB, a processing gain of 15 dB may be a good choice.

Figure 3 plots the minimum P_e as a function of E_b/N_0, when the number of users M is 1, 2, 4, 8, 16 and 32, respectively. One can see that, for a given E_b/N_0, the average error probability for a specific user increases as the number of users increases. This follows from the observation that for any given user as the number of users increases, , the sum of the interference from the other users increases accordingly.

4. Testbed Results

As a part of a feasibility study on the FODMA system, a demonstrator system has been realized. This system was built using standard components and is described in more detail in [5]. In this section the demonstrator setup and the results obtained are discussed.

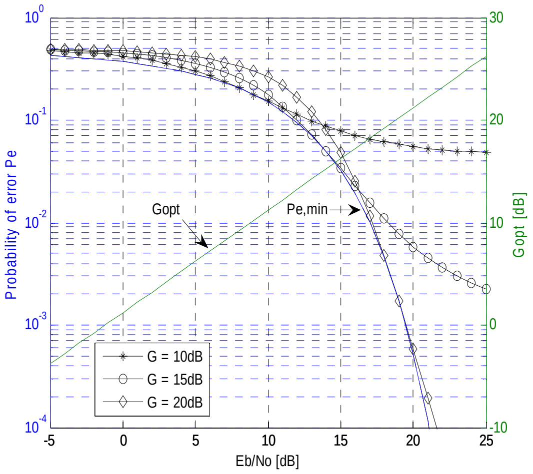

Figure 2: Single-user performance

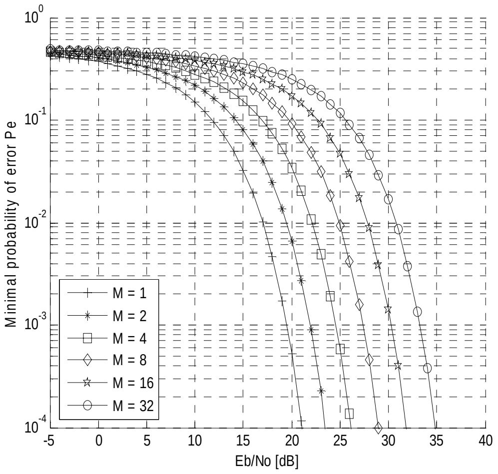

Figure 3: Multi-user performance

A. *Demonstrator Setup*

A schematic overview of the testbed setup is shown in Figure 4. The input noise sequence $c(t)$ is generated by an Agilent E4438C ESG vector signal generator. It delivers a 50 MHz wide BPSK bit sequence, generated by a PN23 pseudo noise generator. The pulse is raised-cosine filtered with $\alpha = 0.1$ and the entire signal $c(t)$ is shifted to a frequency of 2.4 GHz.

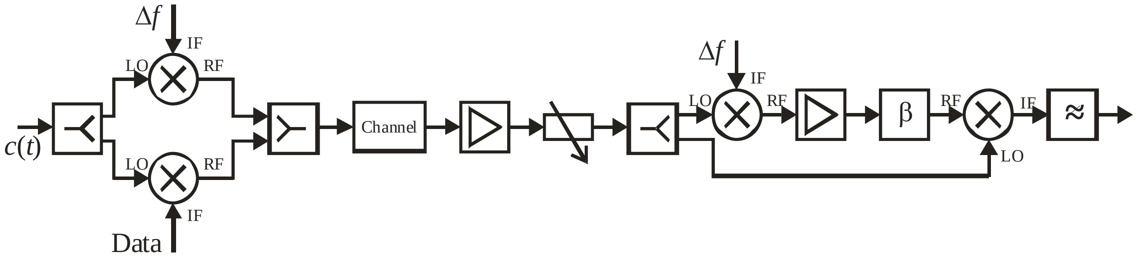

Figure 4: Schematic overview of the FODMA testbed

The applied channel noise is generated by another Agilent E4438C where instead of a BPSK sequence a 4-QAM modulated PN23 sequence of 50 MHz wide is used. The center frequency is also 2.4 GHz. The channel SNR was adjusted by varying the noise output power.

The frequency offset Δf is used both in the transmitter and in the receiver. To avoid severe system performance degradation due to a Δf mismatch both frequency offsets in the testbed are derived from a common source. For the BER measurements a HP 3762 data generator was used in combination with a HP 3763 error detector. The data rate was varied between 50 kbps and 1.5 Mbps to obtain processing gains from 30 to 15.3 dB.

For optimal performance the power of the modulated noise and of the reference noise have to be equal. For this reason we have chosen to apply the frequency shift in the upper branch and the data modulation in the lower branch. Both mixers are of the same type, so that the RF power levels are approximately equal.

The first component at the receiver side is a low noise amplifier with a fixed gain of 25 dB. As a consequence of the varying channel noise levels, the output power of this amplifier will change. To compensate for this, a variable attenuator has been introduced.

In the decorrelation-mixer the received signal is mixed with the back-shifted signal. This second signal has to be in phase with the original signal. For this purpose a phase shifter β has been introduced. The output signal is then lowpass-filtered with a cutoff-frequency f_c = 2.5 MHz and 40 dB suppression above 5 MHz. Following 10 dB amplification, an active variable-cutoff filter with 24 dB/octave slopes and an f_c equal to the data bandwidth filters out the remaining noise (not shown). The output signal of this filter is fed to the error detector.

B. *Results*

In Figure 5 the transmitter output signal, prior to the addition of channel noise is shown. The frequency offset was 3 MHz, so that the resulting spectrum was approximately 56 MHz wide. The power in this frequency band was -10 dBm.

Figure 6 shows the data input and output signals. It can be seen that the main lobe of the output spectrum is hardly affected by the low-pass filtering. Higher frequencies are suppressed effectively.

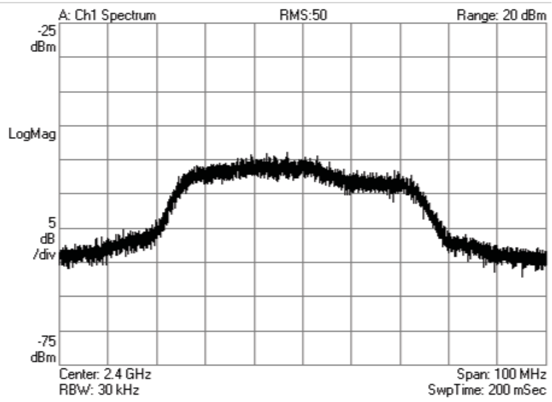

Figure 5: Transmitter output signal

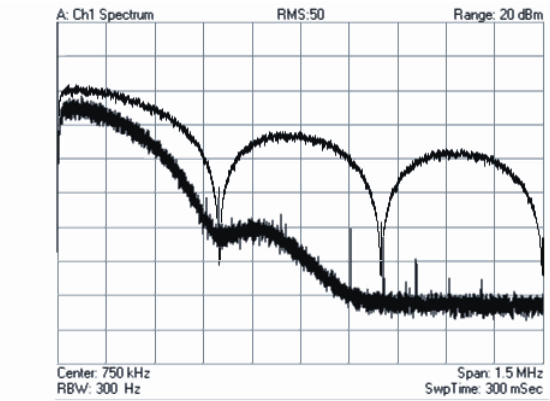

Figure 6: Data in- and output spectrum

In Figure 7 the performance of the system is shown for different processing gains under varying E_b/N_0. The frequency offset was 3 MHz. The dashed lines show the behavior as predicted by theory. It can be seen that, apart from an 8 dB shift, the behavior of the system matches the theory reasonably well. This major difference of 8 dB can be assigned to factors not taken into account in the theoretical analysis. Among these are LO power leakage, noisy components and the overall power levels in the system being close to the noise floor. It can also be observed that the measured error floors are lower than the predicted values. This has been observed in other, comparable systems [3][6]. It can be assigned to the unfulfilled assumption of the input noise being Gaussian.

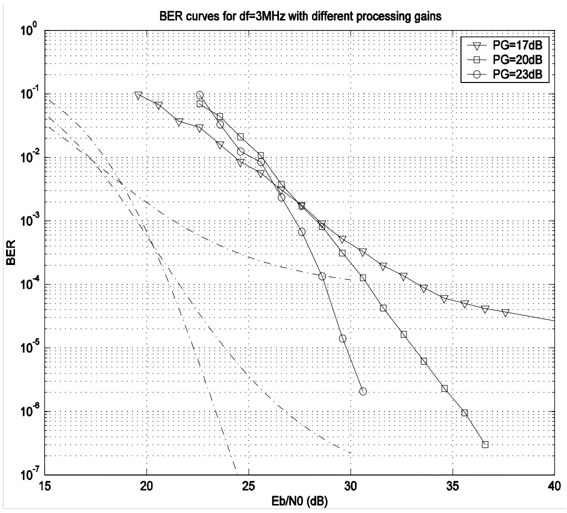

Figure 7: Measured BER as function of E_b/N_0 for different processing gains

5. Conclusions

In this paper, a novel modulation scheme has been presented where the information bearer is based on pure noise. A spread-spectrum transmit-reference scheme has been applied for quick acquisition of the signal in the receiver. The reference signal is separated from the information signal by a frequency offset. Multiplying the received signal with a frequency-shifted version of itself results in de-spreading of the received signal directly to base band.

Analytical expressions show that the BER performance depends on the thermal noise and the self-interference. The latter results from cross-mixing of different shifted versions. The self-interference results in a BER floor that can be reduced by increasing the processing gain.

A testbed operating at 2.4 GHz has been built using discrete components. The measurement results had about 6-8 dB worse noise performance than predicted by theory. However, good correspondence was found in the BER behavior as a function of the processing gain.

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