FM over Impulse Radio UWB

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Abstract—Recent regulatory action provided access to large chunks of spectrum for low spectral power density ultra-wideband communication and sensing devices, yet use of this spectrum currently lags behind expectations. The authors propose a simple migration path suitable for low-cost analog audio and video distribution. It uses FM modulation of the clock signal to an impulse radio pulse generator and a simple receiver based on a rectifier or squaring device which retrieves the FM modulated signal. Using previously developed IR-UWB components (an FCC-compliant monolithic pulse generator, a 3.1–10.6 GHz low-noise amplifier and wideband antennas), plus discrete receiver components, a proof-of-concept experiment was conducted with a 99.4 MHz carrier frequency FM signal. Furthermore it is shown that the receiver performance can be further improved by properly terminating the higher-order signal components after the rectifier.

Index Terms—ultra-wideband, UWB, frequency modulation, impulse-radio, IR-UWB, communications transmission

I. INTRODUCTION

Impulse-radio Ultra-Wideband (IR-UWB) using carrier-free time domain impulses is a simple and energy-efficient concept for utilizing the vast spectral areas opened up by regulatory bodies for low spectral power density communication and sensing systems co-existing with narrow-bandwidth primary users (e.g. 3.1–10.6 GHz in the US, 6–8.5 GHz in Europe). The impulse shape must be chosen to make efficient use of the respective UWB spectral mask, while the impulse repetition rate, modulation scheme and amplitude need to be adjusted to fulfill regulatory spectral power requirements. An investigation of suitable impulse shapes for the UWB masks allocated by the U.S. Federal Communications Commission (FCC) based on the derivatives of a Gaussian impulse can be found in [1]. Commonly, direct pulse-position (PPM) or pulse-amplitude (PAM) modulation by a digital data stream is employed.

In contrast, the use of analog FM-modulated input signals is proposed here, which are fed directly into a UWB pulse generator. Commercially available and very inexpensive low-power FM transmitter and receiver modules can be used together with a minimum amount of UWB components, opening a rapid migration path from e.g. short-range audio links using the FM broadcast band to UWB, where they especially benefit from reduced interference. The system can be made compliant with country-specific regulations by using impulse generators with a pulse shape fitting the respective spectral mask.

II. PRINCIPLE OF OPERATION

The proposed method applies a modulation to the clock signal controlling the repetition rate of the transmitter impulses. In the transmitter, a frequency modulated source (e.g. a low-power FM transmitter module) is directly fed into the UWB pulse generator circuit, where it varies the repetition rate according to the frequency deviation of the input signal. This results in an analog pulse-position modulation, which is shown in a generic form in Fig. 1. Here for simplification a first derivative Gaussian impulse shape was chosen, but the concept works equally with any other UWB impulse shape. The spectral components of this pulse train consist of FM-modulated spectral lines with an envelope defined by the shape.
of the individual pulse. In Fig. 2, an example of the power spectral density of the used impulse train at a repetition rate of 100 MHz can be seen. The resulting spectral lines have a mean distance of 100 MHz and are broadened by the applied frequency modulation.

In the receiver, in order to retrieve the analog information stream from the pulse train, the signal energy contained in the high-frequency spectrum needs to be converted from the UWB frequency band to lower frequencies. This can be done by a simple rectification. In Fig. 3 a simulation example of a frequency modulated and rectified impulse train can be seen, corresponding to the pulse train shown in Fig. 1. The rectified impulse train still carries the frequency modulated information and now has a spectral shape which extends to DC. Its fundamental spectral line is located at the repetition rate of the impulses (100 MHz in the above introduced example). Using a bandpass filter a particular spectral line is then selected, preferably the fundamental or a low-order harmonic. This spectral component carries the complete modulated information. At the output of the bandpass filter a conventional FM demodulator is used to recover the analog information.

This generic description suggests the necessary hardware components. Fig. 4 shows a simplified block diagram. In the transmitter, an FM generating source is connected to an impulse generator, which feeds suitably shaped signals to a wideband antenna. In the receiver, a wideband receiving antenna and a low-noise amplifier is followed by a rectifier for down-conversion and a bandpass filter, which selects the fundamental spectral line. At the filter output an FM demodulator recovers the information signal. The implementation of the components is explained in more detail in the next section.

III. IMPLEMENTATION OF A TEST SYSTEM

In a proof-of-concept experiment, the frequency modulated signal is generated by an FM-modulated laboratory signal generator at a carrier frequency of 100 MHz. This signal feeds directly the input of the impulse generator circuit, a previously published monolithic IC consisting of three building blocks [2]. At the input, a limiting amplifier converts the incoming sinusoidal into a rectangular signal. Its gain and amplitude clipping makes the pulse generation insensitive to the shape and amplitude of the modulating signal. In the second building block, the rectangular signal is differentiated to obtain positive and negative spikes at every rising and falling edge, respectively, of the rectangular signal. The negative spike is subsequently suppressed in a clamping circuit.

In the third building block, an impulse shape similar to a 5th derivative of a Gaussian impulse with a standard deviation \( \sigma = 51 \) ps is generated by a bipolar transistor current switch triggering a damped transient response in an RLC resonator. The IC was realized in a commercial Si/SiGe HBT process with \( f_T = 80 \) GHz. For a measured spectrum of the pulse generator output in comparison with the FCC indoor mask, refer again to Fig. 2. The top part of Fig. 6 exhibits the measured time domain shape of a single pulse.

The incoming frequency modulated sinusoidal signal is thus converted to a position modulated pulse train. The measured spectral components around 6.6 GHz of the frequency modulated Gaussian impulses are shown in Fig. 5. The individual spectra have a frequency difference of 100 MHz corresponding to the applied carrier frequency of the signal source. The modulation frequency and FM deviation were set to 50 kHz each. The modulation becomes clearly visible in the broadening of the spectral lines. A deeper investigation on the spectral shape of position modulated impulses can be found in [3]. The modulated impulses are transmitted via planar monopole antennas described in [2], [4]. In the receiver, following the
receiving antenna, a three-stage UWB low-noise amplifier is employed in as the first stage, again implemented in the aforementioned Si/SiGe HBT technology. It features a 2.7 dB mid-band noise figure, 24 dB gain and a bandwidth exceeding the FCC UWB range. A detailed description of the amplifier IC can be found in [5].

![Fig. 6. Comparison of measured impulse shapes at impulse generator output (upper curve) and bias-tee output (lower curve).](image)

To recover the FM modulated signal from the UWB pulse stream, a single Avago HSCH-5330 Schottky diode is used in our proof-of-concept experiment in a half-wave rectifier arrangement together with two bias-tees allowing an additional variable bias to the diode. The diode was slightly forward biased at 230 mV, which maximizes the spectral output power at the fundamental frequency. The bias-tees both have an insertion loss of 3 dB. The required output band-pass filter is formed here by the high-pass characteristics of the bias-tee and a subsequent low-pass (LP) filter, realized using SMD components on a printed circuit board. The LP filter is of a 7th-order Chebyshev type with a 3 dB corner frequency of 140 MHz. Fig. 8 shows the measured transmission characteristic of the LP-filter. For the final demodulation of the frequency modulated spectral component at the output of the low-pass filter, a Rohde & Schwarz test receiver was used.

IV. MEASUREMENTS

A. Connectorized Components

For a verification of the system concept, the impulse generator is first directly connected to the rectifier by a cable. In Fig. 6 the time domain shape of the impulse at the pulse generator output (top) is compared to the signal after the rectifying diode (bottom). The rectification is clearly evident. The presence of negative voltages in the rectified impulse can be explained by the Schottky diode junction capacitance, which shunts some of the RF energy from the input to the output of the rectifier. The decrease in voltage amplitude by a factor of two is caused by the insertion loss of the two bias-tees. Fig. 7 exhibits the spectral components at the bias-tee output (after rectification, but before low-pass filtering). It can be seen clearly that the spectral components are shifted into the base band (the DC component is blocked by the bias circuit). The rise in spectral content at frequencies from 3–10 GHz is again due to the capacitive coupling across the rectifier diode. Fig. 8 shows the detailed measurement of the spectral components in the lower frequency range, with the low-pass filter response superimposed. The FM modulation can be extracted from any of these spectral lines, where it must be observed that the original frequency deviation is multiplied by the order of the harmonic. Here, the fundamental component at 100 MHz is chosen by the low-pass filter. The remaining frequency modulated fundamental component is then demodulated in the test receiver.

In order to assess the closed system behaviour with an attenuated channel, a step attenuator was placed between transmitter and receiver. The diode voltage was set at its optimum value of 230 mV and not readjusted during the experiment. As can be seen in Fig. 9 a dependence of the observed spectral output power at 100 MHz on the attenuator setting with a slope of approximately 2 dB/db was measured. This can be explained by the approximately quadratic transfer function of the rectifier diode.
B. Wireless Transmission

Wireless transmission was then verified using the antennas and the low-noise amplifier described above. The FM frequency was set to 99.4 MHz and the FM deviation was now set to 60 kHz with a modulating sine wave of 2 kHz frequency. In the test receiver the signal power of the incoming signals was measured within an IF bandwidth of 120 kHz. To obtain an estimate for the maximum transmission distance of the presented wireless test system, the antenna distance was varied in small steps and the received input voltage was recorded. The maximum distance of transmission was defined as the point where the input voltage level drops below the FM threshold.

More precisely, it was experimentally determined at the test receiver input (after the low-pass filter) as the input voltage where the demodulated signal-to-noise ratio (SNR) drops by 1 dB below the linear relationship between the demodulated SNR and the carrier-to-noise ratio at the input. In this case, it was 2.5 dBμV. The SNR was qualitatively determined from the 2 kHz spectral line and the noise floor at the receiver demodulator output using an oscilloscope connected to a computer and a fast Fourier transform. For this measurement, the absolute value of SNR is irrelevant and only the change in SNR was noted. Fig. 10 shows the measurement for the determination of the FM threshold.

The carrier voltage level after the low-pass filter was then recorded for different distances $r$ between transmit and receiving antennas. As Fig. 11 shows, the results closely correspond to the $1/r^2$ dependency expected for free-space propagation. The fact that the loss exponent is slightly below 2 can probably be explained by the presence of the conducting lab bench top. The $1/r^2$ relationship was then used to determine the maximum communication distance before reaching the FM threshold. For the FM deviation and receiver bandwidth chosen, the maximum distance in this proof-of-concept receiver is 3.8 m.

V. Improvements on the Receiver

To improve the receiver performance, and therefore to increase the transmission distance, further amplifier stages or a full-wave rectifier could be implemented within the receiver, which was not done in this simple test system. An additional possibility to improve the receiver performance is to make use of the so far discarded energy of the higher-order spectral components. By this technique of harmonic termination, similar to techniques used to improve the spectral efficiency of power amplifiers, the higher-order spectral components are reflected back towards the rectifier, where their non-linear interaction can further increase the fundamental frequency, provided that the higher-order harmonics arrive with suitable phase.

To utilize this, a high-pass filter is inserted between the low-noise amplifier and the first bias-tee, introducing a highly reflective back termination for the downconverted low-frequency signal content coming from the diode, but allowing the high-frequency content of the UWB impulse coming from the low-noise amplifier to pass through. The second highly reflective termination, this time for the higher-order harmonics, was already introduced by the low-pass filter, which passes only the first harmonic and reflects back all signal content above the cut-off frequency. To obtain constructive interference, an
adjustment of the phases of the higher-order components is necessary, which can be done in its simplest form by inserting transmission lines of suitable length between the high-pass filter and the input bias-tee and between the output bias-tee and the low-pass filter.

Fig. 12. Simulation setup for the proposed improved receiver. A high-pass filter is placed to reflect higher-order harmonics. The transmission line length is used to realize constructive interference.

To show the functionality of this technique, a transient simulation is carried out, as shown in Fig. 12. In this simulation an impulse generator with a repetition rate of 100 MHz is connected to a high-pass filter with a cut-off frequency of $f_{c,HP} = 2.5 \text{ GHz}$. An ideal transmission line is connected between the rectifier and the low-pass filter with a cut-off frequency $f_{c,LP} = 150 \text{ MHz}$. The length of the line is varied, while the spectral power of the 100 MHz first harmonic is monitored at the low-pass filter output. The variation of the spectral power with varying line length (plotted as the phase angle of a 100 MHz signal) can be seen in Fig. 13. The simulation demonstrates the dependence of signal power to line length and therefore indicates that an increase of signal power can be achieved by proper phase adjustment over the proof-of-concept receiver, where the transmission line lengths were randomly chosen. The periodicity of $180^\circ$ indicates the strong contribution of the even-order harmonics. This furthermore predicts an improvement to the receiver of the simple test system, in which the high-pass filter is missing and therefore the reflected energy is not used.

VI. CONCLUSION

The presented paper reports on a new concept of transmitting information in the UWB spectral range by applying a frequency modulated sinusoidal clock signal to an UWB impulse generator. The concept utilizes widely available FM transmitter and receiver circuits, together with a minimum number of additional UWB components. By exchanging the impulse generator circuit, producing a different impulse shape, the system can be made compliant with country specific regulations, e.g. the UWB spectral masks in Europe or Japan. The necessary components were presented and measurements where shown to prove the proper operation of the concept.

Potential and limitations of the concept requires further investigations. It is assumed that the system is robust to narrowband interferences, because out-of-band interference can be easily suppressed by bandpass filtering. Narrowband interferences in the UWB band will be converted by the rectifier to DC and twice the interferer’s center frequency. Both components will be suppressed by the bandpass filter following the rectifier, the distortions due to mixing products between the interferer and the spectral lines of the impulse are currently under investigation. The system can be used by multiple users by choosing different FM center frequencies, similar to conventional FM. The influence of multipath in this system implementation is most probably the same as for conventional FM, but this is as well under investigation.

Following investigations furthermore will focus on the application of different rectifier concepts (full-wave rectification) and the improvement in spectral efficiency. For the latter, first simulations have shown a good improvement potential by properly terminating the higher signal components after the rectifier. Possible applications for the applied concept can be found in short-range communication of analog information, e.g. by using the UWB range for the wireless connection of loudspeakers or for the transmission of music from an MP3 player to a car radio, by connecting the UWB frontend to the available FM radio architecture.

Fig. 13. Simulation of the relative 100 MHz power for various lengths of the transmission line.

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REFERENCES


