Derivation of Circuit Specification for the UWB Impulse Radio Transceivers

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***Abstract*—To satisfy the huge demand for unlicensed handheld wireless networking devices, the Federal Communications Commission (FCC, USA) made the application of ultra-wideband (UWB) technology possible in 2002. Since then an IEEE standard has already been approved for the physical layer of the UWB impulse radio networking devices. Because of the ultra-wideband property the design and implementation of UWB circuits and systems set up an enormous challenge for the circuit designers. Unfortunately, an exact specification has not yet been derived for the circuit designers.**

Starting from the FCC Regulations and the IEEE UWB standard this contribution derives the required specifications for the blocks of UWB transceivers. It shows that if CMOS technology is used then the coverage of UWB impulse radio is limited by the low supply voltage. To overcome this limit more than one UWB carrier pulse is used to keep transmitted energy per bit high enough but to reduce the required voltage swing below the supply voltage. The optimum value of delay to be set between the successive UWB pulses is also determined.

I. Introduction

To simplify the connectivity of IT devices, everything is going to wireless in our days. There is a huge demand for cheap unlicensed wireless networking devices that may operate for years using the same battery and can establish and maintain a data communication network without infrastructure and maintenance. The unlicensed industrial, scientific and medical (ISM) radio bands are already used to fulfill this demand, however, due to the large number of WiFi, Bluetooth and ZigBee devices, the narrow ISM bands are becoming overcrowded. A new technology is required that opens up new frequency bands by re-using the already occupied ones in such a way that the new technology does not cause a harmful interference in the already operating conventional radio systems. The UWB technology supports the frequency re-use by keeping the power spectral density (psd) of the transmitted UWB signal low enough. This contribution focuses on the UWB impulse radio (IR) approach where extremely short impulses are used as carriers.

Based on the already approved FCC Regulations and IEEE standard, the specification for the UWB IR transceivers and their circuits is derived here. The key parameter is the peak pulse amplitude that determines both the voltage swing in the UWB transceiver circuits and the coverage of UWB IR devices. It is shown that the peak pulse amplitude allowed by the FCC Regulations cannot be exploited by the handheld CMOS devices due to the low supply voltage. A solution is proposed to overcome this problem where one bit information is transmitted by a burst of UWB carrier pulses. Finally, the optimum value of delay to be set between the successive UWB pulses is determined.

II. FCC Regulations and Approved IEEE 802 Standard

Federal Communications Commission (USA) permitted marketing and unlicensed operation of UWB radio devices in 2002. The FCC Regulations [1] limits (i) the maximum Equivalent Isotropically Radiated Power (EIRP) that is radiated by the transmit antenna and (ii) the minimum bandwidth of radiated UWB signal. The FCC Regulations say nothing about (i) the type of UWB carrier, (ii) the technique used to generate it and (iii) the modulation scheme. The FCC Regulations give only the rules under which the UWB frequency band may be accessed.

A. FCC Power Limits

To limit the interference caused by an UWB device in an already existing conventional radio system, FCC limits the radiated UWB power in two ways. Both the peak and average powers are limited:

1) "There is a limit on the *peak* level of the emissions contained within a 50-MHz bandwidth centered on the frequency at which the highest radiated emission occurs $\cdots$ That limit is 0 dBm EIRP."
2) The *average* "radiated emissions $\cdots$ shall not exceed" -41.3 dBm EIRP "when measured using a resolution bandwidth of 1 MHz" over the frequency band of 3.1 GHz to 10.6 GHz. "The RMS average measurement is based on the use of a spectrum analyzer with a resolution bandwidth of 1 MHz, an RMS detector, and a 1 ms or less averaging time."

EIRP is the product of the power supplied to the antenna and the antenna gain relative to an isotropic antenna. Note, the FCC Regulations gives not only the limits but also instructions how the power limits have to be measured. That information will be used later to interpret the FCC EIRP limits.

B. Allocated Frequency Band and UWB Bandwidth

The frequency band allocated to handheld UWB radio devices goes from 3.1 GHz up to 10.6 GHz. The UWB bandwidth is defined by the frequency band that is bounded by the frequencies ($f_H > f_L$) where the power spectrum of radiated signal is 10 dB below the peak value. Frequency of peak value may differ from the center frequency.

By definition, the fractional bandwidth is given by

$$BW_{frac} = 2\,\frac{f_H - f_L}{f_H + f_L}.$$

A UWB transmitter is an intentional radiator that, at any time instant, has (i) a fractional bandwidth $BW_{frac} \geq 20\%$, or (ii) a UWB bandwidth $f_H - f_L \geq 500$ MHz, regardless of the fractional bandwidth.

The only already approved IEEE Standard for the UWB impulse radio was elaborated by the IEEE 802 LAN/MAN Standards Committee as an amendment to IEEE 802.15.4–2006 in 2007 [2]. Both narrowband and wideband UWB IR devices have been defined, the bandwidth of the former and latter devices are 499.2 MHz and 1.331 GHz, respectively.

III. Carrier of UWB IR Devices

The UWB carrier pulse is a bandpass signal which can be decomposed into a lowpass envelope and a sinusoidal signal. The IEEE Standard 802.15.4a does not restrict the shape of envelope but the cross-correlation of the envelope with a square root raised cosine reference pulse has to meet two requirements [2]:

- its maximum has to be greater than 0.8 over a specified main lobe width and
- its all other peaks have to be less than 0.3.

Many pulses can be used as UWB envelope. Because of its easy implementation with CMOS technology [3] and easy mathematical handling, the frequency-shifted gaussian pulse is considered here

$$
\begin{aligned}
g(t) &= p(t)\cos(\omega_C t) \\
&= \sqrt{\frac{2Z_0E_b}{k\sqrt{\pi}\,u_B}}\exp\left(-\frac{t^2}{2u_B^2}\right)\cos(\omega_C t)
\end{aligned} \qquad (1)
$$

where $p(t)$ is the lowpass gaussian envelope, $f_C = \omega_C/2\pi$ is the center frequency of the frequency-shifted gaussian pulse, Z_0 is the characteristic impedance over which E_b is measured and u_B is determined by the required 10-dB RF bandwidth $2f_B$ of UWB wavelet

$$u_B = \frac{1}{2\pi f_B\sqrt{\log_{10}(e)}}.$$

To increase the radio coverage, one bit information is transmitted by a burst of UWB carrier pulses. Parameter k in (1) gives the number of UWB pulses used to carry one bit information. In the remaining part of the contribution, $g(t)$ is referred to as UWB carrier pulse.

The *peak pulse amplitude* is obtained from (1) as

$$V_{peak} = \sqrt{\frac{2Z_0E_b}{k\sqrt{\pi}\,u_B}}. \qquad (2)$$

The waveforms and the spectra of the UWB carrier pulses are shown in Figs. 1 and 2, respectively. The upper and lower traces depict the properties of the narrowband and wideband UWB carrier pulses, respectively, defined in IEEE Std 802.15.4a–2007.

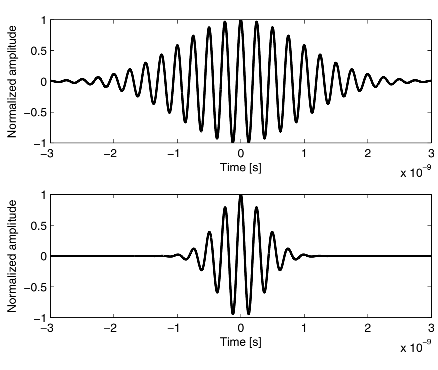

Figure 1. UWB carrier pulses in the time domain for 499.2 MHz (upper trace) and 1.3312 GHz (lower trace) RF bandwidths.

Figure 1 shows that the UWB carrier pulses decrease rapidly as a function of time. The idea of effective pulse width, introduced in spectrum analysis [4], is used to characterize the UWB pulse duration

$$\tau_{eff} = \int_{-\infty}^{+\infty}\frac{p(t)}{V_{peak}}dt = \sqrt{2\pi}\,u_B = \frac{1}{f_B\sqrt{2\pi\log_{10}(e)}}. \qquad (3)$$

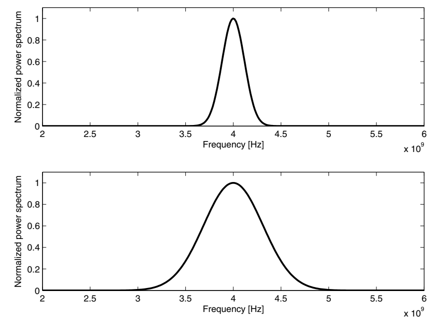

Figure 2. Spectra of UWB carrier pulses for 499.2 MHz (upper trace) and 1.3312 GHz (lower trace) RF bandwidths.

IV. Derivation of Peak Pulse Amplitude

A. Interpretation of FCC Peak Power Limit

The peak radiated emission is defined at the output of a bandpass filter characterized by a bandwidth of $\mathrm{RBW}_{50}^{\mathrm{FCC}} = 50$ MHz and centered on the frequency at which it reaches its maximum. Let this filter be referred to as the FCC filter. The power measured at the output of FCC filter shall not exceed 1 mW.

To express the relationship between the envelope $p(t)$ of the UWB carrier pulse given by (1) and the FCC peak power limit, a lowpass equivalent model for the FCC peak power limit measurement has been developed. In the equivalent model, depicted in Fig. 3, a lowpass filter, the lowpass equivalent of the FCC filter, is driven by the envelope of UWB carrier pulse. The cutoff frequency of lowpass equivalent filter is equal to the half of the FCC filter bandwidth, that is, $\mathrm{RBW}_{50}^{\mathrm{FCC}}/2 = 25$ MHz.

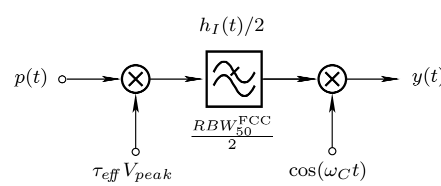

Figure 3. Lowpass equivalent model of the FCC peak power limit calculation.

The excitation $p(t)$, applied to the input of lowpass equivalent model, is a gaussian nascent function that implements a delta function provided that $\sqrt{2}u_B \rightarrow 0$. From an engineering point of view this condition is satisfied when the bandwidth of the gaussian nascent function $p(t)$ is much larger than that of the equivalent lowpass filter.

This condition is always satisfied in UWB IR systems since $f_B \gg \mathrm{RBW}_{50}^{\mathrm{FCC}}/2$. Then, considering a 50-Ω termination, the relationship between the FCC 1-mW peak power limit and the peak pulse amplitude is obtained as

$$P_{peak}^{\mathrm{FCC}} \equiv \{0\ \mathrm{dBm\ EIRP}\} = \frac{y(0)^2}{Z_0} = (\mathrm{RBW}_{50}^{\mathrm{FCC}}\,\tau_{eff})^2\frac{V_{peak}^2}{Z_0}. \qquad (4)$$

B. Interpretation of FCC Average Power Limit

The average power level of UWB emission has to be measured by a spectrum analyzer with a resolution bandwidth of 1 MHz, an RMS detector, and a video filter with 1 ms or less averaging time. The lowpass equivalent model of the FCC average power limit measurement is shown in Fig. 4 where the cutoff frequency of lowpass equivalent filter is equal to $\mathrm{RBW}_1^{\mathrm{FCC}}/2 = 500$ kHz.

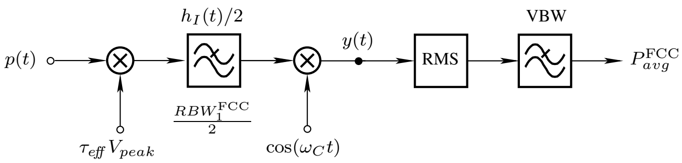

Figure 4. Lowpass equivalent model of the FCC average power limit calculation.

According to the FCC Regulations the average power P_{avg}^{FCC} should not exceed -43.1 dBm EIRP

$$P_{avg}^{FCC} \equiv \{-41.3 \text{ dBm EIRP}\} = \frac{V_{peak}^2}{2Z_0} \, 1.06 \, \text{RBW}_1^{\text{FCC}} \, \frac{\tau_{eff}^2}{T_{bin}} \quad (5)$$

where T_{bin} is the bit duration, the reciprocal value of data rate R_b, and the constant of 1.06 expresses the fact that the RF frequency response of built spectrum analyzers is a gaussian function [4].

V. Derivation of Specification for UWB Circuits

Each UWB transceiver contains many circuits from the transmit power amplifier to the low-noise preamplifier. To develop these circuits, the voltage swings caused by the UWB carrier pulse and the specification for the frequency responses have to be known.

A. An Important Property of UWB Circuits

The models shown in Figs. 3 and 4 highlight a very important and unique property of UWB circuits that cannot be neglected. The conventional communication circuits almost always operate in steady-state, the transient responses of the circuits are generally neglected. The situation is very different in UWB impulse radio where extremely short pulses are used as carriers. Since the bandwidth of UWB pulses is frequently large compared to that of the systems or circuits being excited by the UWB pulse, the excitation may be considered as a *unit impulse* function. The response of the excited circuit is equal to its *impulse response* or, many times, the transient response of excited circuit cannot be neglected.

B. Required Peak Pulse Amplitude

The peak pulse amplitude determines the linearity requirements and the required supply voltage that is crucial in handheld and mobile LR-WPAN/WLAN applications.

Equations (4) and (5) establish the relationship between the FCC Regulations and the peak pulse amplitude. Note, the actual shape of UWB pulse has no effect on V_{peak}, but the data rate, appears in (5).

The FCC limits on the peak pulse amplitude calculated from (4) and (5) are plotted in Fig. 5 as a function of the data rate where the dashed and solid curves show the limits for the narrow- and wideband UWB IR systems, respectively. Observe, the low-rate (LR) UWB systems are *peak power limited*, while the high-rate systems are *average power limited*. The crossing point of the low-rate and high-rate systems is at the data rate of 350 kbps.

The supply voltage of low-cost, low-power CMOS SoC UWB radio systems is less than 1.5 V. The low supply voltage limits the maximum attainable peak-to-peak output voltage swing at the power amplifier output in about 1 V. Therefore, the large peak pulse amplitude allowed by the FCC Regulations cannot be exploited. The low attainable peak pulse amplitude results in a low E_b and, consequently, in a very short radio coverage.

This observation has a serious consequence. The LR UWB IR devices cannot exploit, even theoretically, the FCC peak power limit.

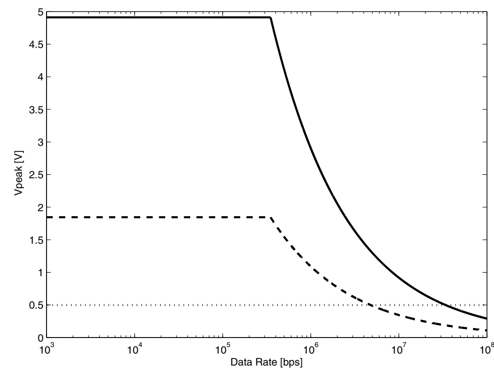

Figure 5. Maximum allowable peak pulse amplitude versus data rate for the bandwidths of 499.2 MHz (dashed curve) and 1331.2 MHz (solid curve). Note, the low-rate and high-rate systems are peak and average power limited, respectively. Dotted curve shows the case when V_{peak} is limited in 0.5 V by the supply voltage.

C. Reduction of peak pulse amplitude

In the low-rate UWB IR systems the required peak voltage amplitude may be reduced considerably while keeping the overall E_b high enough if more than one UWB carrier pulse is used to transmit one bit information. This solution is shown in Fig. 6 where five UWB carrier pulses are used in to transmit one bit information. Recall, parameter k appearing in (1) and (2) was introduced to give the number of UWB pulses used to carry one bit information.

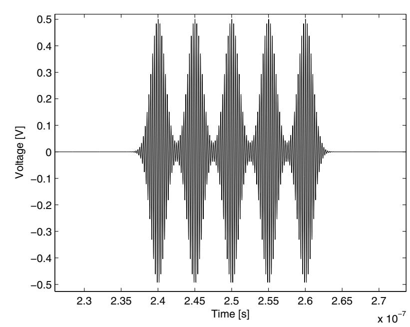

Figure 6. Transmission of one bit using five UWB carrier pulses in a burst.

Consider a LR UWB IR device where $k = 5$. Because of the handheld application, let the peak pulse amplitude be limited in 0.5 V as shown in Fig. 6. Note, the time delay t_{delay} elapsed between two successive UWB pulses is a free design parameter that can be exploited to optimize the parameters of UWB transmitter. Let the effect of time delay be determined first.

Figures 7 and 8 plot the FCC filter output when the time delays between the successive UWB pulses are set to $8\tau_{eff}$ and $2\tau_{eff}$, respectively. The FCC peak limit is shown in both figures by dashed curves. Because the peak pulse amplitudes limited by the supply voltage are identical in the two cases, the two solutions offer the same E_b and, consequently, the same coverage.

Figure 7 shows that if $t_{delay} = 8\tau_{eff}$ then the generated UWB carrier meets the FCC peak power limit with a considerable margin. It means that the interference caused by this UWB transmitter in a conventional receiver remains much below the FCC Regulations.

If the time delay is reduced to $2\tau_{eff}$ then the UWB transmitter cannot satisfy the FCC peak power limit. As shown in Fig. 8, the interference caused is a bit above the allowed peak power limit.

Section V-A already emphasized that, contrary to the conventional communication circuits, the transient responses generated by the UWB excitation cannot be neglected. This effect can be observed in Figs. 7 and 8 where both the steady-state and transient responses of FCC filter can be identified. The total duration of transient response is about 2×90 ns, a much larger value than the duration of one UWB pulse.

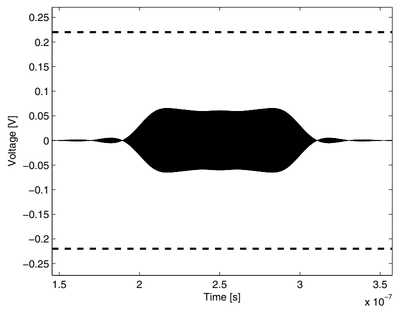

Figure 7. FCC filter output when $k = 5$ and $t_{delay}/\tau_{eff} = 8$. The 1-mW FCC peak power limit is shown by dashed curve.

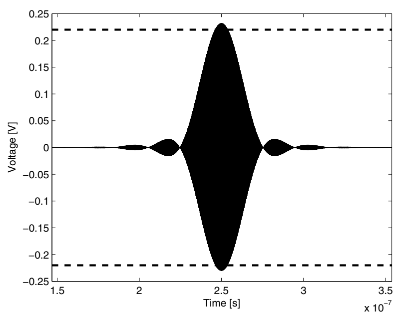

Figure 8. FCC filter output when $k = 5$ and $t_{delay}/\tau_{eff} = 2$. The 1-mW FCC peak power limit is shown by dashed curve.

To find the optimum UWB transmitter configuration, the relationship among the (i) peak pulse amplitude, (ii) time delay between the successive UWB carrier pulses and (iii) number of pulses used to transmit one bit information has to be found. Figure 9 plots the amplitude of UWB carrier wavelet belonging to the 1-mW FCC peak power limit measured at the FCC filter output as a function of k. The parameter is the time delay normalized to the effective pulse width τ_{eff}. The number k of UWB carrier pulses can take only integer values but in order to get an easy-to-use figure, the values belonging to the same normalized delay are connected by solid curves.

Let $V_{peak}^{1\text{ mW}}$ denote the amplitude of UWB carrier wavelet that belongs to the 1-mW FCC peak power limit. As shown by Fig. 9 if $k \geq 5$ then $V_{peak}^{1\ mW}$ has discrete values that heavily depend on t_{delay}/τ_{eff} but that are almost independent of k. Note, the curves in Fig. 9 are almost parallel to the x-axis.

If $k \geq 5$ then the use of Fig. 9 is as follows: First t_{delay} and $V_{peak}^{1\text{ mW}}$ are chosen. The largest amplitude assures the smallest k, that is, the simplest transceiver configuration. However, in certain applications the attainable peak pulse amplitude is limited by the supply voltage.

The required value of E_b is determined by the coverage to be achieved and is obtained from the link budget. After selecting t_{delay} from Fig. 9 and equaling V_{peak} to $V_{peak}^{1\text{ mW}}$, k is obtained from (2).

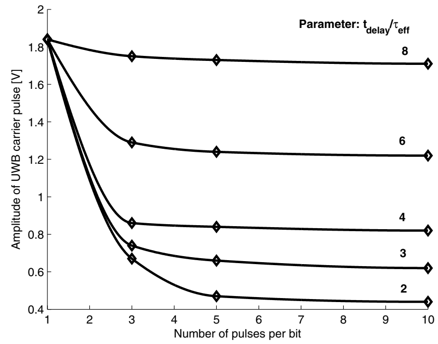

Figure 9. The peak pulse amplitudes of the UWB carrier pulses that belong to the 1-mW FCC peak power limit. The parameter is the normalized time delay t_{delay}/τ_{eff} elapsed between the successive UWB carrier pulses. Its values are 2, 3, 4, 6 and 8 from the bottom to the top.

D. Frequency Responses of UWB Circuits

The circuits used in UWB transceivers are ultra wideband circuits, the bandwidths of the proposed UWB systems are about 500 MHz, 1.3 GHz and 2 GHz. The UWB circuits have to operate in the microwave frequency region going from 3.1 GHz up to 10.6 GHz. There is a very loose specification for the frequency responses of the UWB circuits. The only restriction is given by the FCC Regulations, the variance in the amplitude response has to be less than 10 dB.

Today there is a widely-accepted agreement among the researchers working on UWB IR systems that only the noncoherent receivers are feasible [5]. If noncoherent energy detector-based or autocorrelation UWB receivers are used than the phase response is irrelevant.

VI. Conclusion

Starting from the FCC Regulations and the already approved IEEE 802.15.4a Standard this contribution derived the most important specifications for the constituting circuits of the UWB IR transceivers. It has been shown that in the low-rate handheld CMOS systems the FCC peak power limit cannot be exploited due to the low supply voltage. The low attainable voltage swing limits very strongly the coverage of the UWB IR networking devices. A solution where a burst of UWB carrier pulses is used to transmit one bit information has been proposed and the effect of time delay elapsed between two successive UWB pulses has been evaluated.

Acknowledgment

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