Observations on Low Data Rate, Short Pulse UWB Systems

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***Abstract* – Since the FCC's First UWB Report & Order in 2002, much commercial emphasis has been placed on high data rate applications such as wireless USB, video transfer, etc. This paper addresses the other extreme of low data rate UWB systems which have rather unique properties for certain sensor applications. Starting with the FCC constraints on peak and average power densities, the asymptotic bounds on system performance – EIRP, range and interference potential – are investigated for low PRF UWB system designs.**

***Index Terms* – Electromagnetic measurements, Electromagnetic propagation, Pulse measurements, Transient response, Interference**

I. Introduction

Low data rate, ultra wideband (UWB) systems utilizing short pulse electromagnetic principles have been in use or development for nearly 50 years [1]. At low data rates, these unique, wide bandwidth, waveforms have been shown to be well suited for low probability of detection (LPD) and multipath-immune communications, high resolution radar, and precision geolocation applications [1,2]. While much commercial attention has been focused on high-speed short range wireless applications for UWB, low data rate UWB systems are becoming of increasing commercial interest because of their unique properties – particularly, those of extended range, high energy efficiency and multipath immunity – which have made such systems ideal for such applications as industrial asset and personnel tracking and RFID [2].

What is perhaps not well understood, however, is that low data rate UWB waveforms have very different properties than high data rate waveforms when measured using modern spectral analysis equipment. Since the spectrum analyzer is used in all FCC compliance testing, it is thus of interest to consider how this measurement disparity affects the achievable performance of a "compliant" UWB system.

In Section II, we briefly summarize existing FCC regulations for UWB systems, noting how UWB regulations depart from the FCC's Part 15 general emission limits with respect to peak and average power. Section III relates these peak and average power constraints to both measured and actual UWB power measurements. Maximum available full bandwidth peak power is determined versus transmission rate at various UWB pulse bandwidths. In Section IV, the maximum achievable range is determined for an FCC-compliant UWB emitter as a function of transmission rate. Finally, Section V discusses UWB interference to other systems, again as a function of transmission rate.

II. FCC Part 15 UWB Regulations

Under the FCC's general emission limits for unlicensed devices (47 C.F.R. Part 15, §15.35 and §15.209), power limits are specified in terms of the *full bandwidth* (FBW) peak power (-21.25 dBm) and average power *density* (-41.25 dBm/MHz)[1]. To properly determine FBW peak power, pulse desensitization correction (PDC), in which the FBW peak power is computed from a narrowband power measurement such as made with a conventional spectrum analyzer, was required [3]. The PDC requirement severely restricted the peak power levels permissible under the FCC's general emission limits for short pulse UWB signals, prompting the FCC to consider new regulations to allow such wideband signals to operate under its unlicensed Part 15 rules.

In its February 2002 UWB First Report & Order (R&O), and later in its March 2005 Second R&O [4,5], the FCC added regulations for both ultra wideband (Subpart F) and wideband (§15.250 and §15.252) systems, eliminating the FBW peak power constraint (i.e., PDC correction) and replacing it with a peak power density limitation. Under these new regulations, unlicensed UWB and wideband emitters are not to exceed a peak EIRP (Effective Isotropic Radiated Power) density level of 0 dBm in a 50 MHz bandwidth. The average EIRP density was maintained at -41.25 dBm/MHz or 75 nW/MHz, equivalent to an average electric field strength intensity of 500 μV/m at a distance of 3 meters from the radiating element. For peak measurements, the FCC permits the use of a spectrum analyzer resolution bandwidth (RBW) from 1 to 50 MHz with the peak power density limit for a given RBW expressed as 20 log (RBW/50) dBm.[2]

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[1] We only consider systems operating above 1000 MHz. The FCC' Part 15 general emission limits are slightly different for lower frequency systems.

[2] It is of interest to note that there are actually two FCC Part 15 waivers which either directly or indirectly affect the permissible peak and/or average emission limits. The first waiver, granted in March 2005 to the MultiBand OFDM Alliance Special Interest Group (MBOA-SIG) [6] permits radiated emissions from UWB transmitters to be measured while the transmitter is in its normal operating mode (rather than with frequency hopping turned off as

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Under Subpart F, the minimum permissible transmission bandwidth was specified as 20% fractional (i.e., the ratio of the instantaneous bandwidth to the center frequency) or 500 MHz, whichever is smaller, with both bandwidths specified at the -10dB points of the spectrum. However, commercially available spectrum analyzers typically have much narrower resolution bandwidths than the instantaneous bandwidth required of a UWB emission. The narrower resolution bandwidths of the measurement process prompted the FCC's original requirement for PDC to be performed on power measurements for pulse-type waveforms.

It is important, therefore, to understand the impact of measurements made by a spectrum analyzer on FCC compliance for a given UWB design. The effects of these measurement bandwidth limitations on the maximum permissible power, transmission range and interference potential of a UWB transmission are discussed below. For low data rate UWB systems, it will be shown that the FCC constraints on peak and average power densities permit long range operation with minimal interference.

III. Peak and Average Power Constraints

Let P_{peak} be the full bandwidth peak power of a UWB waveform having pulsewidth τ. The true average power P_{ave} of the waveform is thus given by the relationship

$$P_{ave} = P_{peak}\delta \qquad (1)$$

where δ is the pulse duty cycle. If the UWB signal has a nominal pulse repetition frequency (PRF) of R, then $\delta = \tau R$.

Now suppose that this same signal is measured with a spectrum analyzer having a resolution bandwidth B_R. If $\tau << 1/B_R$, as is typically the case for UWB transmissions, the resolution bandwidth (RBW) filter will "ring" with the filter's characteristic impulse response when excited by a UWB pulse, irrespective of the actual shape of the UWB excitation. More specifically, if $\tau << 1/B_R$, the power spectral density of the input is relatively constant over the bandwidth of the RBW filter, and the output is thus a close approximation to the system impulse response.

From basic Fourier transform theory, this characteristic impulse response has a time duration roughly equivalent to the reciprocal of the filter's bandwidth, namely $\tau_R \sim 1/B_R$. The filtered output pulse is thus effectively stretched in time by the resolution bandwidth filter's impulse response.

If the pulse repetition rate $R<<B_R$ (i.e., low data rate), individual pulses can be discerned at the output of the resolution bandwidth filter since the impulse response dies out prior to the next pulse excitation[3]. In this case, the apparent or measured duty cycle δ_m of the signal is given by the relationship:

$$1 > \delta_m = \tau_R R >> \delta, \quad R<<B_R. \qquad (2)$$

On the other hand, if $R>>B_R$, then the filter output never completely dies down between pulses and the apparent output duty cycle is effectively unity

$$\delta_m \approx 1 \;\; >> \delta, \quad R>>B_R. \qquad (3)$$

See [8] for more properties of high data rate UWB systems.

Note, however, that only the fraction B_R/B_P of the total energy of the pulse will exit the filter, where B_P is the effective pulse bandwidth. By conservation of energy arguments, the peak amplitude P^m_{peak} of the stretched waveform at the output of the resolution bandwidth filter is further reduced so that

$$P^m_{peak}\tau_R = \left(P_{peak}\frac{B_R}{B_P}\right)\tau \qquad (4)$$

or

$$P^m_{peak} = \left(P_{peak}\frac{B_R}{B_P}\right)\frac{\tau}{\tau_R} = P_{peak}\tau^2 B_R^2, \quad R << B_R \qquad (5)$$

where $B_P = 1/\tau$.[4] In this case, the *measured* average power is given by the relationship:

$$P^m_{ave} = P^m_{peak}\tau_R R = P_{peak}\left(\frac{B_R}{B_P}\right)^2 \tau_R R$$
$$= P_{peak}\tau^2 B_R R, \quad R<<B_R.^5 \qquad (6)$$

required under the Part 15 general emission regulations). In this case, the average limit of -41.3 dBm/MHz is unchanged, however the measurement process has been modified for such waveforms. The second waiver, granted in May 2007 to Multispectral Solutions, Inc., permits the use of higher peak power (+12.75 dBm/50 MHz) transmissions under §15.250 (i.e., in the 5925 – 7250 MHz band) for a wide variety of safety-related applications [7].

[3] We consider here the asymptotic cases of $R<<B_R$ and $R>>B_R$.

[4] Note that in (5), the UWB pulse width τ was set equal to the reciprocal of the instantaneous bandwidth B_p. This is a reasonably accurate approximation if B_p is defined as the -3 dB bandwidth [9], but not for -10 dB bandwidth as used by the FCC for compliance testing. The -3 dB bandwidth is also a more appropriate bandwidth to use for a determination of communications range.

[5] We have somewhat simplified the average measurement process. Unfortunately, not all spectrum analyzers utilize the same averaging process. The reader is referred to [10,11,12] for further details.

Note that, for R<<B_R, the *measured* peak-to-average ratio is given by

$$\Xi^m = \frac{B_R}{R} \tag{7}$$

whereas the *true* peak-to-average ratio is

$$\Xi = \frac{B_P}{R} >> \Xi^{\mathrm{m}}. \tag{8}$$

For R>>B_R, the measurement filter effectively sums $R\tau_R$ pulses during the impulse response duration τ_R. In this case, the measured output peak voltage (as measured using the "max hold" feature of the spectrum analyzer as required for FCC compliance testing) is roughly $R\tau_R$ times larger than the measured peak voltage for a single pulse. In terms of measured power levels:

$$P^m_{peak} = (R\tau_R)^2 P_{peak}\tau^2 B_R^2 = P_{peak}\tau^2 R^2, \quad R>>B_R. \tag{9}$$

In summary, the measured average and peak values are given by the relationships:

$$P^m_{ave} = \begin{cases} P_{peak}\tau^2 R B_R & \text{for } \mathrm{R} << B_\mathrm{R} \\ P_{peak}\tau^2 R^2 & \text{for } \mathrm{R} >> B_\mathrm{R} \end{cases} \tag{10}$$

$$P^m_{peak} = \begin{cases} P_{peak}\tau^2 B_R^2 & \text{for } R << B_R \\ P_{peak}\tau^2 R^2 & \text{for } R >> B_R \end{cases}. \tag{11}$$

Note that the measured peak-to-average ratio is essentially unity for R>>B_R as expected.

As discussed above, the FCC mandates that the average radiated emissions from a UWB transmitter satisfy the inequality constraint

$$P^m_{ave} \le 75nW \text{ in a 1 MHz bandwidth}^{6} \tag{12}$$

and that the peak emission satisfy

$$P^m_{peak} \le \left(\frac{B_R}{50x10^6}\right)^2 x1mW \quad \text{for } 10^6 \le B_R \le 50x10^6. \tag{13}$$

Now, for R<<B_R, the FCC average constraint (12) confines the FBW peak power (10) to

$$P_{peak} \le \frac{0.075x10^{-12} B_p^2}{R} \text{ Watts.} \tag{14}$$

Similarly, the FCC peak power constraint (13) confines the FBW peak power (11) to

$$P_{peak} \le 0.001\left(\frac{B_p}{50x10^6}\right)^2 \text{ Watts.} \tag{15}$$

For R>>B_R, it is easy to see that the FBW peak power is limited by the FCC average power constraint (12), yielding

$$P_{peak} \le 7.5x10^{-8}\left(\frac{\mathrm{B_p}}{R}\right)^2 \text{ Watts.} \tag{16}$$

Equations (14)-(16) are shown plotted in Figure 1 below.

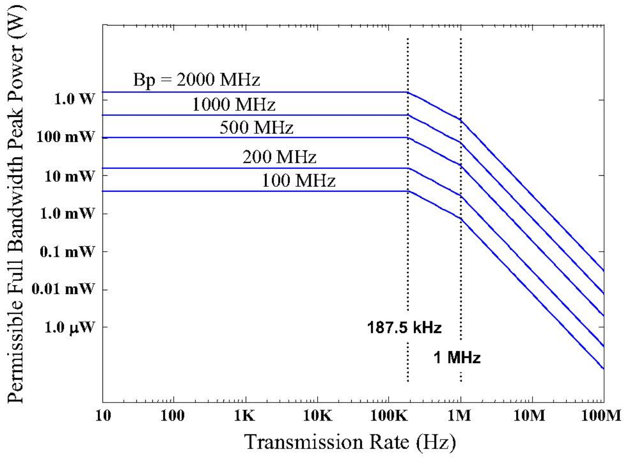

Fig. 1. Full Bandwidth Peak Power Constraint vs. Transmission Rate for Various -3dB Pulse Bandwidths.

An interesting observation can now be made for low data rate UWB systems. The curves for the two FCC constraints (peak and average) cross at R=187.5 kHz, irrespective of pulse bandwidth. Thus, at rates R<<187.5 kHz, the FCC *peak* power constraint essentially dominates and the permissible peak power remains constant irrespective of data rate R. However, at rates R>>187.5 kHz, the FCC *average* power constraint dominates, and the permissible peak power decreases with increasing R. (Note that there is a secondary break at the 1 MHz resolution bandwidth required for the average power measurement.)

Note that, for R << 187.5 kHz, the worst case average power decreases with decreasing R since the maximum permissible FBW peak power is a constant for a given pulse bandwidth. Thus, low data rate systems have a decreasing potential for interference as R decreases – both from a peak power perspective (fewer pulses at a fixed peak power) and from an average power perspective (duty cycle decreases with decreasing R).

[6] According to FCC regulations, the average measurement must be performed in a 1 MHz resolution bandwidth.

For rates R >> 187.5 kHz, both permissible peak and average power levels drop inversely with increasing R also leading to decreased potential for interference, albeit with substantially decreased range of operation.

IV. RANGE

Next consider the range or distance D over which an FCC-compliant UWB pulse can be detected. From the Friis equation for communications range,

$$P_r = \frac{P_t G_t G_r \lambda^2}{(4\pi D)^2} \tag{17}$$

where P_r is the peak power at the receiver, P_t is the peak transmitted power, G_t (G_r) is the transmitter (receiver) gain and λ is the signal wavelength. For an FCC-compliant emitter, $P_{peak}=G_tP_t$ must satisfy each of the inequalities (10) and (11).

Note that the signal-to-noise ratio ξ at the receiver is given by the relationship

$$\xi = \frac{P_r}{kTB_p}. \tag{18}$$

Thus, for R << 187.5 kHz, one obtains the relationship

$$D \le \frac{\lambda}{4\pi(50x10^6)}\sqrt{\frac{B_p G_r}{1000kT\xi}}. \tag{19}$$

Consider a typical operational UWB system operating under FCC Part 15.250 with

λ = 5 cm (6 GHz)
G_r = 12 dBi
ξ = 20 dB.

Range D for such a system is shown plotted in Fig. 2 as a function of -3dB bandwidth B_p and transmission rate R.

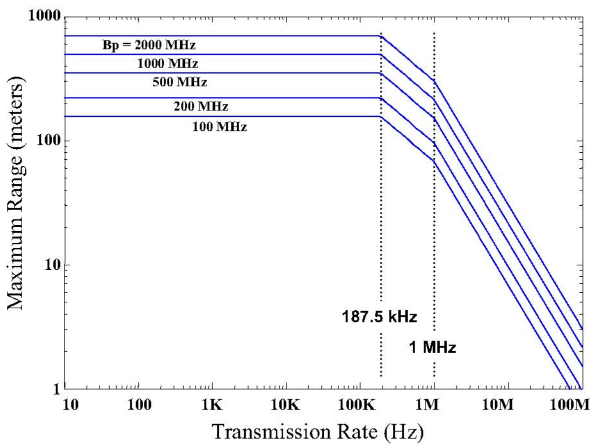

Fig. 2. Maximum Achievable LOS Range vs. Pulse Bandwidth and Transmission Rate for Example 15.250 Compliant System.

As a concrete example, Multispectral Solutions, Inc. (MSSI) *Sapphire* DART UWB-based real time location system (RTLS) operates with an instantaneous -3dB bandwidth of approximately 400 MHz and an average transmission rate well below the 187.5 kHz cutoff. The predicted maximum range of the system, operating at 6.0 GHz, is thus 311 meters. The actual measured system range was 305 meters, in good agreement with the prediction.

V. INTERFERENCE

For a determination of interference potential, it is instructive to compute the average power from a short pulse UWB device that falls within a victim receiver's resolution bandwidth. Given a victim receiver at a distance D_v having antenna gain G_v and resolution bandwidth B_V, the average received interference power P_I can be computed as:

$$P_I = P_{peak}\left(\frac{R}{B_P}\right)\frac{G_v\lambda^2}{(4\pi D_v)^2}\left(\frac{B_V}{B_P}\right) \tag{20}$$

which, for an FCC Part 15 transmission operating at a PRF below 187.5 kHz is:

$$P_I = 10^{-3}\left(\frac{RB_V}{(50x10^6)^2}\right)\frac{G_v\lambda^2}{(4\pi D_v)^2}. \tag{21}$$

It is interesting to compare the maximum communications range D (cf. equation 17) of the UWB device with the range D_v at which a victim receiver observes a ξ-fold increase in its noise floor. Setting $P_r = \xi_0 kTB_P$ in (17), where ξ_0 is the minimum usable signal-to-noise ratio for the cooperative UWB link and $P_I = \xi kTB_V$ in (20), one obtains the relationship:

$$\frac{D_v}{D} = \sqrt{\frac{\xi_0 R G_v}{\xi B_P G_r}}. \tag{22}$$

Note that the interference range relative to the cooperative communications range decreases as the square root of the ratio of PRF to UWB bandwidth. The actual interference range can be determined from (22) and Fig. 2.

For the example in Fig. 2 with a communications signal-to-noise ratio ξ_0 of 20 dB and victim antenna gain at the UWB operating frequency equal to that of the UWB receiver's antenna, one obtains the results in Fig. 3 for the range at which a victim receiver observes an increase in its noise floor equal to kTB_R (i.e., ξ =1). Note that this also assumes a worst case situation in which the victim receiver antenna is directly pointed at the UWB transmitter.

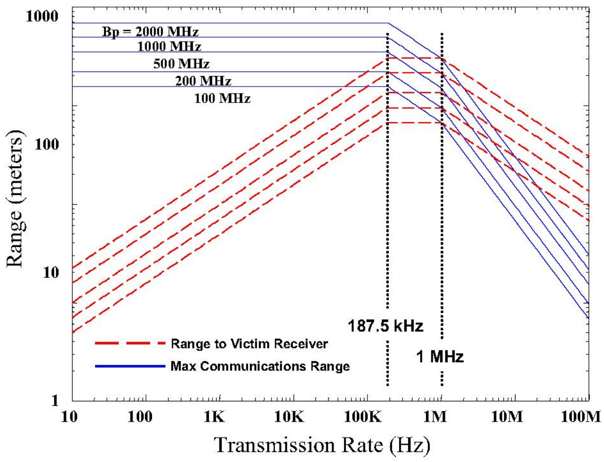

Fig. 3. Communications and Victim Receiver Ranges vs. Pulse Bandwidth and Transmission Rate (see text).

Fig. 3 illustrates an interesting result. For FCC compliant systems operating at PRFs higher than 1 MHz (the bandwidth specified by the FCC for making average measurements), the achievable communications range for a 20 dB signal-to-noise ratio is actually shorter than the range at which a victim receiver observes an average received power from the UWB transmitter equal to its noise floor. For signal-to-noise ratios smaller than 20 dB this effect also occurs, but the transition happens at higher PRFs. This phenomenon is a simple consequence of the manner in which FCC peak and average power measurements are made. For low PRF systems, on the other hand, communications range typically far exceeds the range at which a victim receiver is affected.

VI. Conclusion

Because of the unique properties of pulse power measurements performed using narrowband spectral analysis equipment, low data rate UWB systems have rather interesting properties with respect to their FCC-permissible peak limit, communications range and interference potential. While essentially artifacts of the measurement process, these results are nevertheless critical to a thorough understanding of the FCC limits for short pulse electromagnetic waveforms operating in the low PRF regime. This paper investigated the asymptotic bounds on system performance – allowable EIRP, communications range and interference potential to legacy systems – for low PRF UWB system designs.

Acknowledgement

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